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EXPERIMENTS IN EXTERNAL NOISE REDUCTION OF A SMALL PUSHER-TYPE AMPHIBIAN AIRPLANE

By John P. Roberts and Leo L. Beranek

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SUMMARY

The work reported is part of a program the objective of which is to find practicable ways of reducing the external noise level of light airplanes.

This report covers noise measurements on a representative pusher-type amphibian airplane. The work supplements earlier work by the Aeronautical Research Foundation on the external noise of tractor-type airplanes. Modifications of the pusher-type airplane and noise-measurement procedures used for the present work were similar to those used for the earlier noise study of the tractor-type airplane.

Tests were made (1) with a standard pusher-type airplane; (2) with the same airplane using a four-bladed propeller; (3) with a modified version of the airplane using a geared engine and four-bladed propeller but no exhaust muffler; and (4) with a modified version of the airplane using a geared engine, exhaust muffler, and propellers varying in number of blades from three to eight. Tests were also made on the eight-bladed configuration of the geared and muffled airplane with the muffler relocated so that the exhaust did not pass through the propeller.

For all configurations these tests included sound-level recordings of take-offs and of overhead flights at 100- and 500-foot altitude. They also included analyses of sound-frequency components with the airplane on the ground from a distance of 50 feet and at various positions around the airplane. For some of the configurations sound-level recordings were made for flights at 500-foot altitude passing 3000 feet away. These measurements from 3000 feet away were also made for a standard tractor-type airplane. Finally, frequency analyses were made for the noise of one of the modified configurations of the pusher-type airplane during a flight passing 3000 feet away. Valuable information was obtained during this study concerning methods of external-noise measurement and interpretation of such measurements.

In general, it was demonstrated that significant reduction in the external noise of the pusher-type airplane can be achieved by the use

of slower-turning propellers in conjunction with engine exhaust mufflers. This reduction can be achieved without serious sacrifice in performance if a variable-pitch propeller is used. This result is in agreement with that of previous work on tractor-type airplanes.

With a given tip speed and engine-power output, it was found that increasing the number of propeller blades above four did not decrease the noise level. This result differs from that of previous work on tractor-type airplanes.

Directing the discharge from a muffler so that it passed through the propeller disk did not increase the over-all noise generation under the conditions of the present study. There is evidence to indicate that it actually reduced the noise generation as compared with a location outside the propeller disk.

The noise of the standard ungeared model of the pusher-type airplane was not significantly reduced by the use of a four-bladed propeller in place of the standard two-bladed propeller operating at comparable power, even when the four-bladed propeller had a lower tip speed.

The pusher-type airplane, in both the standard and modified configurations, radiated sound more uniformly in all directions in flight than the tractor-type airplanes. While the maximum noise level in a flight overhead or passing 3000 feet away is about the same for the two types, the lack of sharp directivity in the pusher means that the noise level for the pusher is higher at most measuring positions. The difference in noise generation for the two types tested can be explained by the difference in engine and propeller location and the disturbance of the air flow through the pusher propeller which did not exist for the tractor.

The lack of directivity in the noise of the pusher-type airplanes as compared with the tractor-type airplanes tested means that the pusher types make a disturbing noise for a longer time and at any given time in flight make a disturbing noise over a larger area. In addition, the character of the noise generated by the pusher-type airplanes appears to be more annoying than that of the tractor-type airplanes tested. Both of these conditions mean that the standard pusher-type airplane tested is a noisier airplane than the standard tractor-type airplane tested and the modified pushers are noisier than the modified tractor-type airplanes under comparable flight conditions.

INTRODUCTION

Experiments by the National Advisory Committee for Aeronautics (references 1 to 5) and the Aeronautical Research Foundation (reference 6) have shown that it is both possible and practical to achieve significant reduction in the external noise level of light airplanes by the use of slow-turning multibladed propellers and engine exhaust mufflers. These studies investigated principally the effectiveness of this technique in reducing the external noise of conventional tractor-type airplanes.

The present study was undertaken to determine how effective this technique would be in reducing the external noise of a representative pusher-type amphibian airplane. A second objective was to investigate the effect on the noise level for a geared and muffled pusher-type airplane when the number of blades was increased while maintaining both engine power and propeller tip speed constant. A third objective was to investigate the effectiveness, on the pusher airplane, of simpler modifications for reducing the noise such as omitting the muffler with a slow-turning propeller or increasing the number of propeller blades without reducing the propeller speed or using engine muffling.

The experiments reported herewith were conducted during the years 1948-50 by the Aeronautical Research Foundation under the sponsorship and with the financial assistance of the National Advisory Committee for Aeronautics.

The project was under the general direction of Dr. Lynn L. Bollinger, Executive Director of the Foundation, and under the technical direction of Professors Otto C. Koppen and C. Fayette Taylor of the Massachusetts Institute of Technology and Mr. Arthur H. Tully, Jr., of the Harvard Business School.

Mr. Fred S. Elwell, Administrative Supervisor of the Foundation, coordinated and supervised the project and, in addition, assisted with part of the sound measuring, piloting, and data plotting.

Mr. Joseph Garside, Director of Operations for the Foundation, directed the control of airplane safety and maintenance and piloted the airplane on many occasions.

Mr. William W. Dean, Administrative Assistant of the Foundation, provided assistance in piloting, sound-level measurements, and data plotting during the summer of 1949.

The following individuals and organizations generously contributed equipment and assistance on this project: Aircooled Motors, Inc., lent an experimental geared engine. The Goodyear Aircraft Corp. lent two GA-2 amphibians. The first airplane was converted with the experimental geared Franklin engine, special propellers, and silencers. The second airplane was a standard model GA-2 which was used for sound-level comparison purposes. Additional gratuitous services were extended by this Corporation, namely, structural engineering modifications and engine

changes; also company pilots were provided to ferry the aircraft several times between the Foundation's facilities and their factory. The Maxim Silencer Co. gave the silencers for the experimental pusher airplane. Sensenich Bros. provided all experimental propellers at cost. Mr. Joseph Garside, President of Wiggins Airways, gave use of his company's shops and facilities.

DESCRIPTION OF APPARATUS

Airplanes

The following airplanes were used in this study:

(1) A standard Goodyear Aircraft GA-2 amphibian, equipped with a Franklin six-cylinder, direct-drive engine, rated at 145 horsepower at 2600 crankshaft rpm. The engine on this airplane was equipped with short exhaust stacks pointed straight up. This airplane, shown in figure 1, will be referred to in this report as the standard pusher.

(2) A modified Goodyear Aircraft GA-2 amphibian, equipped with an experimental Franklin six-cylinder, geared engine, rated at 180 horsepower at 3050 crankshaft rpm. The adjustable-pitch propellers used on this airplane were set for the work of the present report so that the maximum power of the engine was approximately 145 horsepower, comparable with the power of the standard pusher. This experimental engine and its planetary gearbox with a 0.632-to-1 ratio is the same as the one used in the experimental tractor reported on in reference 6. It was equipped with a single Maxim exhaust silencer mounted above the engine and exhausting through the propeller. This airplane, shown in figure 2, with the muffler exhausting through the propeller will be referred to in this report as the modified pusher.

This airplane was also flown without the muffler and with the muffler relocated so that the exhaust did not pass through the propeller. These two configurations of the modified pusher will be referred to as the modified pusher, unmuffled, and the modified pusher, muffler relocated. They are shown in figures 3 and 4.

Back-pressure measurements were made on the three different exhaust arrangements for the modified pusher at a point in the exhaust pipe near the engine. The back pressure for the modified pusher, unmuffled, was 3/8 inch of mercury at 2500 rpm, full throttle. The back pressure for the modified pusher with the normal muffler arrangement was $3\frac{1}{2}$ inches of mercury at 2525 rpm, full throttle, and for the modified pusher with the muffler relocated it was $3\frac{3}{8}$ inches of mercury at 2525 rpm, full throttle. Figure 5 is a drawing of the muffler used.

(3) A standard 1948 Stinson Voyager 165, equipped with a Franklin six-cylinder, direct-drive engine, rated at 165 horsepower at 2800 crankshaft rpm. This airplane is similar to the one referred to as configuration 5 in reference 6. It was used during the present measurements to provide data on the noise levels produced by this airplane when flown 3000 feet away since this type of measurement had not been made in the previous work. Figure 6 is a photograph of this standard tractor airplane.

(4) Measurements made for the previous report of the noise produced by both a standard and a modified tractor airplane are presented for comparison with those for the pusher airplane in the present report. Detailed information on these airplanes may be found in reference 6.

Propellers

The standard pusher was first equipped with a two-bladed Aeromatic constant-speed propeller. This propeller was adjusted so that the engine turned at a maximum of 2600 rpm, delivering approximately 145 horsepower. The inset of figure 1 shows the standard pusher equipped with this propeller.

The standard pusher was also flown with a fixed-pitch, solid, four-bladed propeller. This propeller provided maximum- and cruising-power flight operation fairly comparable with that provided by the Aeromatic propeller. It provided poor take-off performance, however, since it operated at a lower maximum speed and power on the ground than an Aeromatic propeller. This propeller is shown on the standard pusher in figure 7.

The modified pusher with the muffler exhausting through the propeller was equipped with three-, four-, six-, and eight-bladed propellers using special wooden blades assembled in one of two hub adapters. These propellers were ground-adjustable and, as previously mentioned, were set to provide a maximum power comparable with the 145 horsepower of the standard pusher. Figure 8 shows each of these four experimental propellers mounted on the modified pusher. The three-bladed propeller may also be seen on the modified pusher in figure 2.

The modified pusher, unmuffled, was flown only with the experimental four-bladed propeller. This configuration is shown in figure 3. The modified pusher, muffler relocated, was flown only with the experimental eight-bladed propeller and is shown with this propeller in figure 4.

In order to simplify the problem of referring to the various airplane propeller configurations each has been assigned a configuration number in a numbering system which is a continuation of that used in the earlier report (reference 6). Table I shows these configuration numbers and gives engine, muffler, and propeller information for all the configurations (including those of the earlier work) referred to in this report. It may be noticed in table I that reference is made to two configurations of the standard tractor. In the present report the comparisons between the pusher and tractor for overhead flights and ground analysis use data for the standard tractor (configuration 1) from the previous report (reference 6). The new measurements made for the flights 3000 feet away were made using configuration 5, since configuration 1 was no longer available. The difference between these two configurations is in the propellers used. Configuration 1 had a two-position propeller which was always used in the steeper, or cruising, pitch. Configuration 5 had a solid wooden propeller. The difference between these two configurations is not very great but was considered important enough so that it could not be neglected.

Blade-form curves for the various propellers used on the pusher airplanes are shown in figures 9 to 12. Blade-form curves for the propellers used on the tractor airplanes may be found in reference 6.

Sound-Measuring Equipment

The sound-measuring equipment used in this study consisted of:

(1) Sound-level meter, General Radio Co., with its microphone mounted inside a double cloth wind screen at the end of a 25-foot extension cable

(2) Sound analyzer, General Radio Co.

(3) Graphic level recorder, Sound Apparatus Co., a high-speed level recorder

(4) Magnetic tape recorder, Magnecord Inc., used with sound-level meter and sound-level-meter microphone.

The interconnection of instruments used for the take-off and flight measurements and for the ground analysis is shown in figure 13, and the frequency responses of the sound-level meter and sound-level meter and sound-analyzer combination are shown in figure 14. The interconnection of instruments used for the magnetic tape recordings and for the subsequent analysis of the tapes is shown in figure 15.

Flight-Control Apparatus

A Dewey and Almy Chemical Co. "Kytoon" captive balloon was used to aline flight altitude. In addition, a sensitive altimeter was carried in the airplane to help the pilot maintain flight at a constant altitude when he was not near the Kytoon altitude marker. The airplane carried the usual instruments including, particularly, the engine tachometer which was used to observe engine speed during all sound measurements.

TEST PROCEDURE

Location of Tests

All sound measurements and performance tests on the standard and modified pusher airplanes were made at Norwood Memorial Airport, Norwood, Mass., between December 1948 and January 1950. Figure 16 is a map of this airport and the surrounding country, showing the course over which the airplane was flown for the flight measurements.

The normal test procedure was divided into three parts, namely: Take-off measurements, flight measurements, and ground analysis. In addition, some measurements were made of flights at an altitude of 500 feet from a distance of 3000 feet. These measurements will be discussed separately.

Take-Off Measurements

For the take-off measurements, the pilot was instructed to make his take-off so that he was just leaving the ground as he passed over a marker 50 feet from the sound-level-meter microphone. In order to simulate the performance of a constant-speed propeller, the pitch of the experimental ground-adjustable propellers was set so that the engine at full throttle would turn at 2500 rpm at the start of the take-off. During the take-off the pilot gradually reduced the throttle setting so that the engine speed throughout the entire take-off did not exceed 2600 rpm. For the take-offs with the solid four-bladed propeller of configuration 7, take-offs were made with a full throttle setting throughout since the maximum speed for these take-offs did not exceed 2600 rpm.

During each take-off the peak reading of the sound-level meter was observed and continuous records were made, on the graphic level recorder, of the sound level from the start of take-off until the sound of the airplane died down into the background noise. A reference mark was made on the sound-level records by momentarily shorting the input to the graphic level recorder as the airplane passed over the marker 50 feet from the microphone. Four take-offs were made for each airplane-propeller configuration tested. Two of these were measured with the sound-level meter set for flat weighting and two, for 40-decibel weighting.

Flight Measurements

For the flight measurements, the pilot was instructed to make level flights in a straight line, first at 100 feet and then at 500 feet, over the course shown on figure 16. This course extended about 6000 feet in each direction from a point on the north-south runway. The pilot alined his altitude on each flight by reference to the Kytoon altitude marker. Since the flights were all in a line with one side of the north-south runway it was a simple matter to make all flights accurately over the specified course.

At each altitude, eight flights were made at maximum power and eight, at cruising power. The pitch of the experimental ground-adjustable propellers used on the geared engine was so adjusted that the full throttle setting of the engine in level flight would provide 145 horsepower at 2500 rpm corresponding to the maximum rating of 145 horsepower at 2600 rpm of the standard pusher with the Aeromatic propeller. In the case of the standard pusher with the solid four-bladed propeller (configuration 7), no adjustment was possible. With this configuration the full throttle setting gave a maximum-power speed of approximately 2750 rpm and cruising was chosen as 2450 rpm. Propeller tip speeds, engine powers, and other engine and propeller information for all configurations tested are shown in table II.

Measurements of the sound level of these overhead flights were made from a point on the north-south runway directly beneath the flight path. For each flight the peak reading of the sound-level meter was observed, and continuous records of the sound level were made. For each engine power, at each altitude, four flights were measured with the sound-level meter set for flat weighting and four, with the 40-decibel weighting. All sound-level records were marked with a reference mark by momentarily shorting the input to the graphic level recorder as the airplane passed overhead.

Ground Analysis

For the ground analysis, the airplane was chocked tail down on the ground with the propeller hub over the center of a compass rose laid out on one of the taxying strips at the airport. For these measurements the pitch of the experimental ground-adjustable propellers was set as it was for the take-off measurements, that is, so that the engine turned at 2500 rpm at full throttle. The pitch of the adjustable four-bladed propeller of configuration 9B was set on a different day from the day it was tested. On the day the ground tests were made it would turn at a maximum of 2475 rpm, but it was decided that this slight variation in speed was not serious enough to warrant the long job of resetting the propeller pitch. The maximum speed obtainable with the solid four-bladed propeller of configuration 7, during the ground analysis, was approximately 2125 rpm.

Measurements were made of the over-all level and the significant frequency components present in the noise of the airplane with the microphone 50 feet from the propeller hub. After the measurement was completed for the position directly in front of the airplane, the microphone was moved 30° along the 50-foot circle and measurements were again made. This procedure was repeated for each 30° on both sides of the airplane with the exception of the 180° position which was omitted because of the propeller slipstream.

Measurements from 3000 Feet Away

In addition to measuring the noise produced by flights directly over the sound-level-meter microphone, certain configurations were measured at a distance of 3000 feet from the flight path. For these measurements, the pilot was instructed to make flights at 500-foot altitude, eight at maximum power and eight at cruising power, over the same course used for the overhead measurements. Propeller pitch settings and engine powers and speeds for these flights were the same as those used for the overhead flights.

The sound-measuring instruments were set up at the east end of the east-west runway at a distance of 3000 feet from the nearest point of the flight path. For each engine power four flights were measured with the sound-level meter set for flat weighting and four were measured with the 40-decibel weighting. A reference mark was made on the sound-level records as the airplane passed the airport beacon tower.

Analysis of Noise of Airplane in Flight

In order to get an analysis of the noise of one of the configurations in flight, for comparison with its ground analysis, a magnetic tape recorder was used. These flights were made at 500-foot maximum power over the usual flight course using the same propeller pitch, engine power, and speed as for the overhead flights. The instruments were set up at the location used for the measurements from 3000 feet away, and the noise of the airplane was recorded on magnetic tape. Peak readings of the sound-level meter were observed for each flight. The tape recording was provided with a reference mark by shorting the input to the tape recorder as the airplane passed the airport beacon tower. These tape recordings were made using flat weighting of the sound-level meter.

Analysis of the sound recorded on the tape was made with the analyzer used for the ground analysis. Several short sections of the recordings of two different flights were cut out of the tape and spliced together forming a continuous belt. This belt of tape with its recording of about $3\frac{1}{2}$ seconds of flight noise was then run through the tape recorder continuously. The resultant repeating short sample of the noise of the airplane was analyzed to determine the important frequency components present in the noise.

PRECISION

Successive measurements of the length of the Kytoon nylon line and correlation of the Kytoon altitude indications with that of a sensitive altimeter carried in the airplane indicated that airplane altitudes were held within ±10 percent. This variation should correspond to a variation of ±1 decibel in the sound-level measurements.

It will be noted that sound-level measurements of similar flights under supposedly similar conditions sometimes showed large differences. It is believed that the major part of such differences was real and was due to variations in atmospheric conditions, terrain, and so forth. This problem is more fully discussed in the section "Discussion of Results."

Laboratory calibration showed that the sound-level-meter error did not exceed ±1 decibel. A reasonable estimate of reading errors under field conditions appears to be about ±1 decibel. The two errors combined would give a maximum error in the sound-level measurements of ±2 decibels, aside from those errors arising at the level recorder.

Because the peak readings of the level recorder were assumed to be those read simultaneously on the sound-level meter, the error in them would still be ±2 decibels. For data depending on recorder readings considerably lower than the peak readings it is not possible to determine the error but, since the machine is generally accepted for work of this kind and was kept in good running order, it is believed that this error was probably not over ±4 decibels.

Accurate calibration of the tape recorder was not possible in the limited time available for its use. In the play-back of the tape recording the level was calibrated approximately by comparison of the peak output of the recorder with the peak reading of the sound-level meter during the flight recorded. When the recordings were made some trouble was experienced with variation of the sensitivity of the tape recorder as a result of variation in the output voltage of the vibrator power supply. It is likely that the sensitivity of the instrument was quite constant during play-back, but no definite information is available on any sensitivity variations which occurred. For this reason, the absolute levels indicated for the analyses of these recordings may have an error of as much as ±5 decibels. The amplitudes of the various frequency components relative to each other were probably not affected by the sensitivity variations.

Frequency responses for the sound-level meter and sound analyzer shown in figure 8 were determined at the Massachusetts Institute of Technology Acoustics Laboratory. Interpretation of the readings of the sound analyzer was made by using these curves. Instrumental errors in the sound analyzer are probably within ±2 decibels, but the actual levels presented in the ground analyses are subject to somewhat larger errors in some cases because readings frequently had to be made of levels that fluctuated as much as 10 decibels. This problem was particularly severe with the higher harmonics of the propeller, so the levels indicated for these higher harmonics cannot be considered more accurate than ±6 decibels.

METHOD OF PRESENTING RESULTS

Sound measurements were made on the eight configurations of the pusher airplane described in table I. Measurements were also made on configuration 5 of the standard tractor. In addition, averages of measurements on configurations 1, 2A, 2B, 2F, 2C, and 2D of the tractor, made for the previous report (reference 6), are presented here for comparison with the pusher measurements. The results of these measurements on the pusher and tractor airplanes are presented in eight series so that the effect of different variables may be considered separately. These eight series are as follows:

Series A: Series A is a comparative study of the external noise of a standard pusher with an Aeromatic propeller (configuration 6) and a modified pusher using experimental three-, four-, six-, and eight-bladed geared propellers (configurations 9A, 9B, 9C, and 9D) in conjunction with an exhaust muffler. These measurements were all made at comparable maximum powers, since the pitch of the experimental propellers was set separately for ground and flight measurements to give performance comparable with that of the Aeromatic propeller in both situations. (See figs. 17 to 30.)

Series B: Series B is a study of the effect of muffler installation on the external noise of the four-bladed, geared-drive pusher airplane. This series compares the modified pusher, unmuffled (configuration 8), with the modified pusher (configuration 9B) as used in series A with the muffler exhausting through the propeller. The same four-bladed experimental propeller was used with each configuration at comparable powers and tip speeds. (See figs. 31 to 35.)

Series C: Series C is a comparison of two muffler locations on the modified pusher using the eight-bladed propeller. This series compares the modified pusher (configuration 9D) as used in series A with the exhaust passing through the propeller and the modified pusher with the muffler relocated so that the exhaust did not pass through the propeller (configuration 10). (See figs. 36 to 40.)

Series D: Series D is a comparison of the ground analyses at 1900 and 2500 rpm of the four-bladed, modified pusher, unmuffled and muffled (configurations 8 and 9B). (See fig. 41.)

Series E: Series E is a comparative study of the external noise of the standard pusher using an Aeromatic propeller (configuration 6) and a solid four-bladed propeller (configuration 7). (See figs. 42 to 46.)

Series F: Series F is a comparison of the external noise levels of the standard and modified pusher configurations studied in this report with the noise of the standard and modified tractors studied in the earlier report (reference 6). (See figs. 47 to 49.)

Series G: Series G includes measurements from 3000 feet away of the standard tractor (configuration 5); the standard pusher (configuration 6); the modified pusher, unmuffled (configuration 8); and the modified pusher, muffled, with the four-bladed propeller (configuration 9B). (See figs. 50 to 53.)

Series H: Series H is a frequency analysis of the noise of the modified pusher, muffler relocated (configuration 10), passing 3000 feet away. This analysis from magnetic tape recordings is compared with the ground analysis for this configuration at the same speed and power. (See fig. 54.)

With the exception of the measurements from 3000 feet away, the results of all flight measurements are presented in the form of graphs in which the sound level is plotted against horizontal distance from microphone to airplane. For the measurements from 3000 feet away, the results are plotted in terms of sound level against the horizontal distance of the airplane from the point on its flight path nearest to the sound-level-meter microphone. The records for all flights at both 100- and 500-foot altitudes are plotted to 5000 feet either side of the zero point. Negative distances plotted to the left of zero correspond, in all cases, to the airplane approaching, while positive distances to the right of zero correspond to the airplane going away. As in the previous report (reference 6) it was decided to use the data taken with the flat weighting of the sound-level meter for the flights at 100-foot altitude and the data taken with 40-decibel weighting for the flights at 500-foot altitude. This means that the plotted data for the two altitudes are not directly comparable. This choice provides data taken with flat weighting for sound levels reaching 90 to 100 decibels and data taken with 40-decibel weighting for sound levels from 45 to 70 decibels. It was felt that this procedure would provide the most meaningful data.

It is worth noting that the graphs of these flights, showing sound levels against horizontal distance, are not corrected for the finite velocity of sound. In other words, the sound level shown when, for example, the airplane was 3000 feet from the zero point of the graph is actually the sound level at the microphone at that time. Since that sound took some time to reach the microphone, it was actually generated when the airplane was somewhat farther away as it approached, or nearer when it was going away. This correction would make the largest difference in the measurements from 3000 feet away. For instance, the noise generated in these flights by the approaching airplane when it was 3000 feet from the nearest point of its flight path would reach the microphone when the airplane was about 2300 feet from the nearest point. The records, as plotted, indicate what an observer at the measuring position would hear and it is evident that the absence of the correction has no effect on comparisons between different configurations moving at the same velocity and measured from the same point. Correction has been made for the finite velocity of sound for the graphs of figures 53 and 54.

For the take-off measurements, it was not possible to plot the sound level against distance since the airplane was constantly changing its velocity; therefore, the sound level was plotted against time. The data taken with flat weighting of the sound-level meter have been used in plotting take-off sound levels.

Information from the ground analyses is presented in the form of polar plots of the over-all level and the amplitude of each significant harmonic component present in the noise of the airplane. Ground analyses were all made with flat weighting of the sound-level meter.

The analyses of the tape recordings, and the ground analyses compared with them, are plotted in separate graphs for each analysis which show sound level against frequency. These graphs indicate the level of each important harmonic frequency component present in the noise analyzed.

In presenting the data for series A, B, C, E, and G a standard procedure is followed. In each series the basic data, consisting of separate graphs for each configuration of that series in each measurement condition, are presented first. These data are followed by comparative plots in which averaged curves for each configuration are compared, for each of the measurement conditions. For the ground analyses the comparative plots present separate comparisons of the over-all levels, engine fundamentals, and propeller fundamentals for each of the configurations of the series. In series D and H only basic data are presented since for these series it was felt that the most useful comparison could be made by studying the data in this form rather than by trying to plot data for different configurations on the same graph. Series F compares averaged data from the present report with averaged data from the earlier report (reference 6).

DISCUSSION OF RESULTS

Series A. Comparison of Standard and Modified Pusher Airplanes (Configurations 6, 9A, 9B, 9C, and 9D)

Take-offs.- The results of the take-off measurements for the five configurations of series A are shown in figure 17. Each of the five graphs shows sound level against time for each of two successive take-offs. Averages of the two curves shown in each of the five graphs are presented together for comparison in figure 23.

In figure 17, the differences between the records taken under supposedly identical conditions indicate the degree of reproducibility achieved between flights made on the same day. Since the flights with different configurations were made on different days with different atmospheric conditions, the comparisons shown in figure 23 are subject to larger uncertainties. An additional problem was introduced by the necessity of comparing the fixed-pitch (ground-adjustable only) propellers of the modified pusher with the Aeromatic constant-speed propeller of the standard pusher. With the Aeromatic propeller at full throttle the take-off started at 2500 rpm and increased to a maximum of 2600 rpm. As previously explained, the experimental propellers were set for 2500 rpm (145 hp) at full throttle at the start of the take-off and the pilot was instructed to limit the speed to 2600 rpm during the take-off run. This procedure was found to be difficult, however, and it is therefore likely that the 2600-rpm limit was exceeded during some of the take-offs. This would afford a reasonable explanation of why the maximum level of the three-bladed, geared propeller on the modified pusher (which was measured first when this technique was new) is nearly as high as that of the standard pusher (fig. 23).

If the high peak for the three-bladed take-off is ignored, the average curves of figure 23 show the standard pusher to be from 5 to 10 decibels noisier than the average of the four modified configurations. Comparing the various modified configurations, it appears that the three-bladed configuration (9A) was 2 to 3 decibels noisier than the average of the modified configurations, at positions away from the take-off point, while the four- and six-bladed configurations (9B and 9C) were slightly quieter than the average. The curve for the eight-bladed configuration (9D) falls between that for the three and those for the four- and six-bladed configurations. Considering the difficulty of maintaining accurate control of the take-offs, however, it is probably not reasonable to ascribe much significance to these small differences.

Flight measurements.- The results of the flight measurements, for the five configurations of series A, are shown in figures 18 to 21. Figure 18 presents the basic data for each of the configurations for the maximum-power flights at 100-foot altitude. Figure 19 presents the data for 100-foot cruising power; figure 20, the data for 500-foot maximum power; and figure 21, the data for 500-foot cruising power. Each graph shows sound level against horizontal distance for four successive flights. Averages of the four curves shown in each of the five graphs of figure 18 are presented for comparison in figure 24. Similarly, averaged curves for the other flight conditions are presented in figures 25 to 27.

It can be seen from figures 18 to 21 that successive flights with the same airplane, at the same power and altitude, sometimes produced nearly identical successive sound-level records. At other times the difference between successive flights was as much as 10 or 15 decibels at certain points. This variation in the sound level of successive flights and the occasional large fluctuations in individual sound-level records were noticed in the earlier work (reference 6). During the present study, it appeared as the work progressed that these fluctuations could only be the result of atmospheric conditions. It was very clear that the fluctuation in a single record was not a product of the terrain or of stray reflections, because all flights were made over the same course in the same way, while the fluctuations were very different on different records. Furthermore, evidence from the earlier work (reference 6) showed that more violent fluctuations were observed on windy days and that the magnitude of the fluctuations tended to increase with an increase of the horizontal distance of the airplane. All these things suggested that turbulence and temperature and wind velocity gradients in the air might be major causes of the observed fluctuations in the sound-level records.

As a result of this evidence, it was decided to make sound-level measurements only when the wind was 5 miles an hour or less. It was found that information about the wind conditions near the altitude of the 500-foot flights could be obtained from the Blue Hill weather observatory located at an altitude about 600 feet above that of the Norwood airport and about 3 miles away from it. A combination of the report from Blue Hill, the pilot's report of turbulence, and the visual observation of the behavior of the Kytoon altitude marker gave a fairly clear picture of what the wind and turbulence conditions were during each series of flight measurements. Correlation of this information with the amount of fluctuation in the sound-level records revealed that the best conditions for testing did not occur when there was dead calm. Apparently, when the air was very calm the airplane began to encounter its own turbulence, in successive flights, as a result of flying repeatedly over the same course. Additional trouble with fluctuation was also experienced on calm sunny days because of turbulence due to uneven heating of the ground and the resultant thermal air currents.

The best test results were obtained when the sky was overcast, so that there was little radiant heating of the ground, and when there was a 2- or 3-mile-an-hour wind across the flight path. Apparently, in this case the air was smooth, and the turbulence in the wake of the airplane, due to one flight, drifted away from the flight course quickly enough so that the airplane was always flying through undisturbed air. The variable which best correlated with the fluctuation observed in the sound-level records was the pilot's report of air conditions. The pilot generally reported rough air when there was a large amount of fluctuation in the sound records. Furthermore, when the sound records were exceptionally free of fluctuation, the pilot noticed exceptionally smooth flying. Occasionally, however, when the pilot noticed smooth flying, some slow fluctuation was observed in the sound records. This seemed to be particularly true on calm days when it seemed likely that the airplane was flying through its own turbulence.

Another problem that must be considered in making sound-level measurements of overhead flights is the problem of the existence of relatively uniform gradients of temperature or wind velocity. Such gradients cause a refraction of sound propagating through them (see reference 7). This refraction may cause sound levels measured several thousand feet away from the source to differ considerably from what they would be with uniform atmospheric conditions. Furthermore, if the abnormal refraction is stable there will be little indication that it is occurring. It appears that in order to reduce the uncertainty in measurement caused by the problems of turbulence and abnormal gradients it would be necessary to make several series of measurements on different days with different atmospheric conditions and average all the results.

Since the numerous flight measurements of the present report could not be repeated on different days, these two problems lend an element of uncertainty to the results of the flight measurements, especially for the sound levels measured when the airplane was 3000 or 4000 feet away.

Even with these variables, however, the averaged comparative plots (figs. 24 to 27) show considerable similarity in the shapes of the sound-level records for the different airplane-propeller configurations. Figure 27, in particular, shows a great similarity in the shapes of the sound-level records for the four modified configurations.

An interesting feature of the flight records at 500 feet is the absence of a definite peak at the overhead position. This is in marked contrast with the corresponding records of the earlier work (reference 6). The difference is presumably due to the shielding effect of the fuselage in the case of the pusher-type airplane (with the overhead mounting of the engine, figs. 1 and 2), which was absent in the case of the tractor (with a nose mounting of the engine, fig. 6). A comparison of the averaged flight records for the pusher and tractor airplanes is made in the discussion of series F and this difference in shape is discussed more fully there.

As was the case with the take-off measurements, the flight measurements show a distinct separation between the curves of sound-level variation for the standard pusher and these curves for the modified pushers, without showing differences in the modified configurations which lie in the order of the number of blades. For the flight records, the three-bladed configuration (9A) appears to be one of the quietest and the eight-bladed (9D), one of the noisiest. There is certainly no evidence to indicate that it would be desirable to use a six- or eight-bladed propeller on the pusher in an attempt to quiet it. On the contrary, it was the opinion of everyone that heard the various modified configurations that the eight-bladed propeller made the most annoying noise. The high-pitched whine of the eight-bladed configuration was particularly noticeable at a distance when the sound levels involved were such that the ear could hear a high-pitched sound as louder than a low-pitched one of the same intensity. Another reasonable objection to the sound of the eight-bladed configuration was that it did not sound like a normal airplane. This feature might call attention to its presence, when it might not otherwise be noticed.

Ground analyses.- The results of the ground analyses for the five configurations of series A are shown in figure 22. Each of the five polar plots shows sound level against position around the airplane, for the over-all level and significant harmonic components. Figure 28 compares the polar plots of the over-all levels for each of the five configurations. Figure 29 makes a similar comparison of the engine fundamentals, and figure 30 compares the propeller fundamentals. For each configuration the frequency referred to as the engine fundamental is three times the engine crankshaft speed, while the propeller fundamental is simply the tip-passage frequency. Since the over-all level for the standard pusher exceeded 110 decibels for certain positions around the airplane, the basic data for this configuration and the comparative plot for the over-all levels have been plotted so that the outer circle of the polar coordinates corresponds to 120 decibels. The remaining polar plots have been plotted so that the outer circle corresponds to 110 decibels in order that the detail at levels below 90 decibels may be clearly shown.

It may be seen in the plot for the standard pusher (configuration 6) in figure 22 that the over-all level for the test conditions used is largely determined by the level of the propeller fundamental. At only three positions does the engine fundamental exceed the propeller fundamental, and at these positions it is only slightly louder. At the 90° position on the right, the engine fundamental was so much lower than the propeller noise that it could not be picked out on the analyzer. It would appear that the addition of a muffler to the standard pusher (configuration 6) without other modifications would not result in an appreciable reduction of the noise generation at 2500 rpm on the ground.

The ground analysis for the three-bladed, modified pusher (configuration 9A) in figure 22 shows a great predominance of the propeller components over the engine fundamental. Furthermore, the over-all-level curve corresponds very closely in shape to the curve for the propeller fundamental. The muffler on the modified configuration (9A) evidently is effective in reducing the engine noise to the point where it is not significant for this test condition.

For the four-bladed propeller on the modified pusher (configuration 9B) the engine noise was so low that it could not be picked out on the analyzer except at two of the measuring positions. For this reason it has been omitted from the polar plot of figure 22. For this configuration, as for the three-bladed configuration, the over-all level is very similar in most positions to the propeller fundamental. The only significant exception is the 150° position on the right where the over-all level is 8 decibels greater than the strongest harmonic component. At this measuring position a large amount of nonharmonic noise was observed, providing a fairly uniform background noise indicated on the analyzer from about 250 to 1000 cycles per second and only a few decibels lower than the amplitude of the third harmonic.

This uniform, nonharmonic noise, which seems to be an exaggerated vortex noise, appears again in the analysis of the six-bladed configuration of the modified pusher (configuration 9C, fig. 22). In this case it was of sufficient amplitude to mask the third harmonic of the propeller. This vortex noise was very pronounced for the positions in front of and behind the airplane, but at the side the harmonic tip-passage frequency was still nearly as loud as the over-all level.

The eight-bladed propeller on the modified pusher (configuration 9D, fig. 22) produced a little more of this vortex noise. In most of the positions around the airplane the noise did not sound particularly like a conventional airplane whine but like an unpleasant tearing noise. Although this noise was not so loud as that of the three-bladed configuration (9A), it seemed particularly annoying. For the 150° position on the right for the eight-bladed configuration, the analyzer indicated a sound level from 83 to 87 decibels throughout the frequency range from 250 to 1050 cycles per second. Above the frequency of 1050 cycles per second the level of this noise decreased and it appeared that there was a rather sharp upper limit to its frequency spectrum. This upper frequency limit is a characteristic of the vortex noise commonly noticed on tractor-type airplanes when the propeller tip speed is reduced (references 3 and 8). The vortex noise generated by the pusher type seems to be similar to that for the tractor airplane, except that it occurs at a much higher noise level for a given tip speed and power.

The comparative plot of the over-all sound levels (fig. 28) shows a well-defined separation of the curve for the standard pusher (configuration 6) and the curves for the various configurations of the modified pusher (9A, 9B, 9C, and 9D). In addition, there seems to be a tendency for the sound level to decrease with an increase in the number of blades. Another interesting change with the increasing number of blades is the change from the condition where the propeller noise, predominant on the sides, is the loudest noise to the condition, with the eight-bladed propeller, where the positions near the nose and tail are noisiest because of the predominant vortex noise.

The comparative plot of the engine fundamentals (fig. 29) shows how effective the muffler was in reducing noise occurring at three times the crankshaft frequency. Differences in the engine fundamentals for the various modified configurations which had the same muffler and engine installations (9A, 9B, 9C, and 9D) are not clearly understood. They may be partly the result of some sort of intermodulation phenomenon in which energy at the engine fundamental frequency is converted to energy at a frequency which is the sum or difference of two frequencies present in the noise of the airplane. This phenomenon has been discussed in the earlier report (reference 6). Sum and difference frequencies have been noticed at certain positions in the ground analyses for the present report, affording evidence that this type of intermodulation does occur on this airplane as well as on the tractor airplane. Since in the modified configurations of series A the exhaust from the muffler is being chopped at the propeller tip-passage frequency, the nonlinear conditions necessary for the production of sum and difference frequencies are almost certainly present.

The comparative plot of the propeller fundamentals (fig. 30) shows once again a separation between the standard (configuration 6) and the modified (configurations 9A, 9B, 9C, and 9D) pushers. There also appears to be a difference between the shape of the curve for the propeller fundamental of the standard pusher and the general shapes of the propeller-fundamental curves for the modified configurations. In the propeller fundamentals, there is a definite tendency for the level to decrease with an increase in the number of propeller blades. This effect would be expected from Gutin's theory, although it did not show up clearly in the over-all levels and in the flight measurements. The lack of agreement with the Gutin theory in the over-all levels of the ground analysis is probably a result of the increased vortex noise with the six- and eight-bladed configurations. The lack of agreement with the Gutin theory in the flight measurements might also be explained by an increase in vortex noise for the six- and eight-bladed configurations, but there is evidence to indicate that this is not the correct explanation. Further information on this problem is presented in the discussion of the flight analysis of series H and in the general discussion of all the results.

Series B. Effect of Installing a Muffler on Four-Bladed, Geared-Drive Pusher (Configurations 8 and 9B)

Take-offs and flight measurements.- The basic data for the two configurations of series B for take-off and flight are shown in figures 31, 32(a), and 32(b). The data for configuration 9B are, of course, the same as those for 9B in series A, but they are presented again in series B for convenience. A similar procedure is employed throughout the rest of the data.

Averaged curves for the take-off and flight measurements are compared for the two configurations of this series in figures 33 and 34. No particular comment seems necessary on the basic data. The records for the modified pusher, unmuffled (configuration 8), at 500-foot altitude show considerable fluctuation at distances of several thousand feet, but this problem has been discussed in the discussion of the flight records for series A. The comparative plots show significant differences between the external noise levels of the unmuffled and muffled modified pusher. The averaged curves for the take-offs show a difference averaging 5 to 8 decibels between the two configurations. The muffler evidently reduced the take-off noise. This result is in agreement with the measurements of the over-all levels for the ground analyses.

The comparative plots for the flight measurements do not show such a marked separation between the curves for the unmuffled and muffled pusher. A maximum difference of about 5 decibels occurs near the overhead position for the records at 100-foot maximum power, 100-foot cruising power, and 500-foot maximum power. For the flights at 500-foot cruising power no such difference was observed. This discrepancy is probably explained by the use of the 40-decibel weighting network for the flights at 500-foot altitude. The change in the relation between the curves for the two configurations when the 40-decibel network was used may be the result of changes in the relationship between the harmonics and the fundamental of the engine noise with the reduction in speed. It might also be the result of changes in the relationship between engine and propeller noise with the reduction in speed. Reference to table II on page 14 of reference 9 shows that changes in the relationships between the fundamental and the harmonics of the engine noise do occur with changes in engine speed.

Ground analyses.- The ground analyses for the unmuffled and muffled modified pusher (configurations 8 and 9B) are presented in figure 32(c). Comparison of the over-all levels, engine fundamentals, and propeller fundamentals from these analyses are presented in figure 35. The ground analysis for configuration 8 (fig. 32) shows that the propeller fundamental and engine fundamental are about equally important in the noise of the unmuffled, geared pusher running at 2500 rpm on the ground. The engine fundamental predominates slightly in front of and to the rear of the airplane, while the propeller fundamental predominates at both sides.

In the ground analysis for the muffled configuration (9B, fig. 32) the engine fundamental was measurable at only two positions so it has been omitted from the basic data. The comparative plot of the engine fundamentals shows to what extent the engine noise was reduced by the muffler. In the two positions where the engine fundamental of the muffled configuration was measurable it was 20 decibels lower than that for the unmuffled configuration. It was probably at least this much lower for those positions where it could not be observed in the ground analysis.

The comparative plot of the over-all levels from the ground analyses (fig. 35) shows a significant difference in the shapes of the curves for the unmuffled and muffled configurations. The unmuffled configuration was louder at all measuring positions than the muffled configuration, and in addition the level for the unmuffled configuration was nearly constant all the way around the airplane. The over-all-level curve for the muffled configuration shows the shape characteristic of the propeller fundamental curve, with the maximum levels occurring at the 90° positions on both sides. The difference between the radiation pattern for these configurations does not appear to be in agreement with the results of the flight measurements which showed the unmuffled configuration to be noisier than the muffled one only near the overhead position of the flight path. It might be expected that the overhead position of the flight path would most nearly correspond to the 90° position of the ground analysis, but it was at this position that the minimum difference existed between the two configurations in the over-all levels of the ground analyses. This discrepancy cannot be explained satisfactorily with the available data. It must be noted that, as previously mentioned, the take-off measurements are consistent with the results of the ground analysis. This would suggest that there is a difference between the radiation characteristics of the airplane operating at maximum power on the ground and operating at the same power and engine speed in flight. This conclusion seems reasonable if the location of engine and propeller with relation to the hull and wings of the pusher airplane is considered in conjunction with the positions from which the indicated noise levels were measured. For the ground analyses and the take-off measurements the sounds radiated to either side are measured. For the flight measurements near the overhead position, the sound underneath the airplane is measured. Figures 1 and 2 show why these positions present a different view of the principal sources of noise on the airplane. Since the engine and propeller are shielded by the hull and the wings when the airplane is near the overhead position for the flight measurements, it is not surprising that the relationships between the noise of different configurations observed in the ground analysis does not hold for the peak levels measured overhead.

It is not so clear why there should be a difference between the results of the ground analyses in front of and behind the airplane and the results of the flight measurements when the airplane was several thousand feet away either approaching or going away. These discrepancies between the results of the ground analyses and the flight measurements occur throughout the data of the present report and have previously occurred in other measurements of this nature (reference 6) and in unpublished data taken by the staff of the Electro-Acoustic Laboratory, Harvard University, 1940-1945, under the general direction of Dr. L. L. Beranek.

The comparison of the propeller fundamentals from the ground analyses of the unmuffled and muffled pusher (fig. 35) shows a difference between the curves for the two configurations. Since the same propeller was used on both configurations and operated at very nearly the same speed and power it is not evident why there should be such a difference. Series B was intended to study the effect of adding a muffler to the unmuffled configuration while holding other variables constant; however, the propeller is involved in the muffler installation because the exhaust coming out of the muffler passes through the propellers (see figs. 2 and 8). This might be expected to increase the noise generation at the propeller tip-passage frequency since the blades of the rotating propeller slice through the rapidly moving stream of exhaust gases. Actually the ground analyses showed the propeller noise generation to be less for the muffled configuration than for the unmuffled.

It appears that the exhaust passing through the propeller reduces noise generation at the tip-passage frequency of the propeller. This can be explained if the propeller blades slicing through the column of exhaust gas produce a source of noise of an intensity comparable with that of the normal propeller noise. In this case the pressure wave coming from the vicinity of the tip of each propeller blade will be a maximum at the same time that the pressure wave produced as the blade cuts through the column of exhaust gas is a minimum. This effect provides two sources of noise at the tip-passage frequency which are out of phase and may partially cancel each other, at least for certain directions of radiation around the airplane. This would cause a reduction in the noise at the tip-passage frequency which could be quite significant at some positions if the two sources are of nearly the same magnitude. Evidence to support this hypothesis is also found in the data of series C where the modified pusher with the eight-bladed propeller and the exhaust passing through the propeller is compared with the same engine-propeller configuration with the muffler relocated so that the exhaust did not pass through the propeller. In this case, as in the similar comparison of series B, the configuration with the exhaust passing through the propeller had lower levels for the propeller fundamental than the configuration in which the exhaust did not pass through the propeller (see fig. 40). In addition, the ground analysis showed the second harmonic of the propeller to be almost as loud as the fundamental for the configuration where the exhaust passed through the propeller but showed it to be considerably quieter than the propeller fundamental for the configuration with the muffler relocated. This suggests a relative reduction in the propeller noise generation at the tip-passage frequency when the exhaust passes through the propeller. Unfortunately, this clear-cut difference in the relationship between the propeller fundamental and second harmonic in the ground analysis did not appear in the analysis for series B, where a reduction in the relative level of the propeller fundamental would be expected to occur on the configuration with the exhaust passing through the propeller. Furthermore, it must be remembered that a reduction of as much as 8 or 10 decibels cannot be explained by the hypothesis of two sources, if the source produced by the propeller chopping the exhaust does not make almost as much noise as the normal propeller noise. Calculations have been made of the magnitude of velocity variation which would have to be introduced in a 2-inch column of exhaust to produce a second source sufficiently intense to produce a cancellation reduction of 10 decibels. These calculations show that a peak-to-peak velocity variation of about 30,000 centimeters per second or approximately 1000 feet per second would be necessary for this large cancellation under the assumed conditions. It is evident that this much variation could not be produced in a column of exhaust gas moving at a velocity certainly not exceeding 500 feet per second. It does seem reasonable, however, that a cancellation of somewhat less than 10 decibels might occur since this would not require so large a variation in velocity. Furthermore, the assumed conditions may be sufficiently modified, under the actual operating conditions, so that the calculations do not present a fair picture of the noise generation by the propeller chopping the exhaust.

The evidence on this subject is thus inconclusive, and further study would be necessary to determine whether the suggested solution to the problem presented is the correct one.

Series C. Effect of Relocating the Muffler on Eight-Bladed, Geared-Drive Pusher so That Exhaust Did Not Pass through Propeller (Configurations 9D and 10)

Take-offs and flight measurements.- The basic data for the two configurations of series C, for the take-off and flight measurements, are shown in figures 36, 37(a), and 37(b). The data for the modified pusher, muffler relocated (configuration 10), at 500-foot cruising power (fig. 37(b)) are of particular interest since the measurements were made under the best test conditions encountered throughout the entire series of measurements for this report. For these records the maximum difference between successive records at any point is 4 decibels, and the average maximum difference is about 2 decibels. Comparison of these records of successive flights at 500 feet with the records for other configurations in this flight condition will reveal the unusual consistency of these records for configuration 10. These measurements were made just after sunset on a day when there was a very slight wind across the flight path and the sky was partially overcast. These conditions provided what the pilot described as perfectly smooth air and provided sound-level records which were particularly smooth and regular. These records provide additional confirmation of the theories advanced in the discussion of the flight records of series A about the sources of the fluctuations usually encountered in flight records.

Averaged curves for the take-off and flight measurements for the two configurations of this series are compared in figures 38 and 39. With the exception of the take-off records the modified pusher with the muffler exhausting through the propeller (configuration 9D) averages slightly quieter than the modified pusher with the muffler relocated (configuration 10). This difference is small enough so that its existence is not clearly established. Since this difference does occur for all flight measurements it may be statistically a significant difference, but it is certainly not a very important one. The results of the take-off measurements show the modified pusher with the muffler relocated to be slightly quieter, but these results are not in agreement with the results of either the flight measurements or the ground analyses. The measured difference is small and probably not significant.

The measurements for series C were made on the eight-bladed configuration of the modified pusher because it was expected that any difference in the noise generation of the airplane caused by relocating the muffler so that the exhaust did not pass through the propeller would be largest with the greatest number of propeller blades. The measurements show that the configuration with the exhaust passing through the propeller is, if anything, slightly quieter than the configuration with the muffler relocated. Since this is true, there seems to be no reason why a muffler used on this airplane, under the conditions for which it was tested, should not be mounted above the engine in the position of configurations 9A, 9B, 9C, and 9D. On the pusher airplane this mounting position appears to afford the simplest installation.

Ground analyses.- The ground analyses for the modified pusher (configuration 9D) and the modified pusher, muffler relocated (configuration 10), are shown in figure 37(c). Comparison of the over-all levels, engine fundamentals, and propeller fundamentals from these analyses are presented in figure 40.

An interesting difference is immediately evident between the ground analyses for configuration 9D, with the exhaust passing through the propeller, and configuration 10, with the muffler relocated. The ground analysis for configuration 10 does not show the wide separation between the over-all-level curve and the curves for the harmonic components of the engine and propeller noise that was observed for configuration 9D. It was pointed out in series A, where the analysis for configuration 9D was discussed, that the over-all level for this configuration was much greater than the strongest of any of the harmonic components of the engine or propeller noise. This separation between the over-all-level curve and the curves for the harmonic components was accompanied by a high level of nonharmonic noise between the frequencies of 250 and 1050 cycles per second. In the ground analysis for the modified pusher with the muffler relocated so that the exhaust did not pass through the propeller (configuration 10) some nonharmonic noise was also noticed, particularly at the 150° positions; however, this nonharmonic noise occurred at a level several decibels below the level at which it occurred for configuration 9D. It is obviously the lower level of the nonharmonic vortex noise for configuration 10 that explains the difference between the ground analyses of configurations 9D and 10.

The comparison of the over-all levels from the ground analyses for the two configurations of this series shows very little difference between the curves. There is a slight predominance of the over-all level for the configuration with the exhaust passing through the propeller (9D) at the front and to the rear of the airplane. At the 90° positions the configuration with the muffler relocated is slightly noisier.

The comparison of the engine fundamentals for the two configurations shows a significant difference between the two curves. The muffler, as used in configuration 10, allowed much more engine noise to be radiated than it did for configuration 9D. Two possible explanations of this phenomenon are as follows: First, it is quite possible that the configuration of muffler and exhaust pipes used in the relocation of the muffler produced a system in which some resonance at the exhaust frequency occurred at 2500-rpm engine speed. The difference in length of exhaust pipes from the two sides of the engine may have been a contributing factor to the reduction in efficiency of muffling (see fig. 4). Second, it is possible that intermodulation between engine and exhaust frequencies, for configuration 9D where the exhaust was chopped at the propeller tip-passage frequency, converted some of the energy at the engine fundamental frequency to energy at a frequency which was the sum or difference of engine and propeller frequencies. As previously mentioned, these sum and difference frequencies have been observed in some of the analyses.

The comparison of the propeller fundamentals for the configurations of series C has been mentioned in the discussion of the comparable plot in series B. It was suggested there that the reduction of noise at the propeller tip-passage frequency, when the exhaust passed through the propeller, might be explained by considering the normal propeller noise and the noise generated by the propeller chopping the column of exhaust as two sources which are 180° out of phase. It is interesting to note, in this connection, the high level of vortex noise for configuration 9D with the exhaust passing through the eight-bladed propeller. As is shown by the comparison of the over-all levels for configurations 9D and 10, the reduction in the level of the propeller fundamental where the exhaust passed through the propeller is balanced by an increase in the generation of the nonharmonic vortex noise. Since the over-all levels in either case are about the same, the change in the character of the noise is the only significant difference. There does not seem to be any particular reason for preferring one type of noise to the other.

A frequency analysis of the noise generated by configuration 10 in flight is presented in the discussion of series H. The results of this flight analysis are quite different from the results of the ground analysis for this configuration. For this reason the conclusions above must be restricted to operation on the ground. An analysis of the noise of configuration 9D in flight would be needed to show whether it produces as much nonharmonic noise in flight as it does on the ground.

Series D. Comparison of Ground Analyses at 1900 and 2500 rpm for Four-Bladed, Geared-Drive Pusher, Unmuffled and Muffled (Configurations 8 and 9B)

When the ground analyses were first made for configurations 8 and 9B they were made with the propeller pitch set as it was for the flight measurements. This measurement provided a ground analysis at 1900 rpm, full throttle, for each of these configurations. It was subsequently decided to reset the ground-adjustable propellers and make the ground analyses for all the configurations at 2500 rpm, full throttle, so that they would be more nearly comparable with the ground analysis for the standard pusher with the Aeromatic propeller. Examination of these analyses at two different speeds seemed interesting enough to make it worth presenting the four analyses for comparison. These four polar plots are shown in figure 41. No comparative plots are presented since the differences are easily seen in this presentation of the basic data.

A comparison of the ground analyses for the unmuffled pusher (configuration 8) at the two speeds shows that the noise at the engine exhaust frequency is almost exactly the same for the two engine operating conditions. Since for both conditions the engine was operating at full throttle and, therefore, maximum manifold pressure, this result is not surprising. Similar results were measured for a similar engine by Davis and Czarnecki (reference 9, table II). The propeller noise generation is very different, however, for the two conditions of operation. This result was expected since both the engine power and the propeller tip speed are reduced at the lower speed (see table II herein). This reduction in propeller noise, without a corresponding reduction in the engine noise, means that the engine noise which was only about equally as loud as the propeller noise at 2500 rpm is predominant at 1900 rpm. It is probably generally true, even for engine operating conditions which are not so extreme as the full-throttle operation at 1900 rpm, that operation at lower engine speeds will be accompanied by an increasing importance of engine noise. In the case of configuration 8, where the engine noise is as loud as the propeller noise at 2500 rpm, this would mean that operation at lower powers and speeds would produce a condition where the engine noise would predominate. These relationships must be considered if the decision is to be made whether the addition of a muffler to the modified pusher would be desirable.

It will be noted in the ground analysis for configuration 8, at 1900 rpm, that a harmonic component at $4\frac{1}{2}$ times the crankshaft frequency attributable to the engine was observed at all measuring positions around the airplane. Since this component was fairly important at some positions, it has been plotted. A similar component at $4\frac{1}{2}$ times the crankshaft frequency was noticed in the ground analysis for configuration 8 at 2500 rpm, but it was only measurable at about half of the measurement positions. This component was as loud during operation at 1900 rpm as it was at 2500 rpm and, in some positions, louder. The engine-noise analyses by Davis and Czarnecki (reference 9) have also showed this component to be an important one in the noise of an unmuffled engine.

Comparison of the ground analyses for the muffled pusher at 1900 and 2500 rpm shows that, with the engine noise reduced by the muffler, the over-all level is reduced by the reduction in propeller noise at the lower power and speed. The muffler is sufficiently effective at this lower speed and engine exhaust frequency so that the propeller noise is still the predominant component of the noise at 1900 rpm.

Comparison of the ground analyses for configurations 8 and 9B, at 1900 rpm, does not show the large difference in propeller noise generation that occurred with these two configurations at 2500 rpm (see series B). Furthermore, at 1900 rpm, configuration 9B makes more propeller noise than configuration 8, where there is a difference. This is in contrast with the greater propeller noise of configuration 8 at 2500 rpm. This difference in propeller noise generation suggests that the exhaust passing through the propeller in configuration 9B is not producing a second source of noise of sufficient magnitude to cause the cancellation at the propeller frequency hypothesized in the discussion of operation at 2500 rpm in series B. Since the exhaust moves at a somewhat lower velocity at 1900-rpm engine speed, however, this difference may still be consistent with the hypotheses of series B.

Series E. Effect of Replacing Aeromatic Propeller with a Solid Four-Bladed Propeller on Standard Pusher (Configurations 6 and 7)

Take-offs and flight measurements.- The basic data for the two configurations of series E, for take-off and flight measurements, are shown in figures 42, 43(a), and 43(b). Averaged curves for the take-off and flight measurements are compared for the two configurations of this series in figures 44 and 45. In considering the data for this series it must be remembered that configuration 7 used a solid wooden propeller which had a diameter 10 inches less than that of the Aeromatic propeller of configuration 6. This meant that configuration 7 could not be operated under conditions comparable with the conditions for configuration 6. Table II shows that maximum-power operation provided the most comparable conditions for the two configurations. In this operating condition the powers were approximately the same, the speed for the four-bladed configuration was slightly higher than that attained by the Aeromatic propeller, and the tip speed was slightly lower. The operating conditions for the ground analysis and take-off measurements were quite different for the two configurations, speed, power, and tip speed for the four-bladed configuration being considerably lower than for the two-bladed Aeromatic.

These differences in operating conditions explain some of the differences that appear in the comparative plots. For the take-offs the higher power and propeller tip speed of configuration 6 explains the higher noise level throughout the take-off for this configuration. The comparison for the flights at 100-foot maximum power (fig. 44) shows very little difference between the two configurations. This result is not in agreement with Gutin's theory of propeller noise generation since the powers were comparable, while the tip speed of the four-bladed propeller was lower than that of the two-bladed Aeromatic. Theoretically, a four-bladed propeller should be quieter, at the same tip speed and power, than a two-bladed propeller, and the reduced tip speed of the four-bladed propeller should make it even quieter. Evidently this theory which is based on the assumption of propellers turning in undisturbed air does not apply to propellers operating under the conditions for the pusher airplane where the propeller blades turn through air which has been disturbed by passing around the engine nacelle and over the hull and wing surfaces (see figs. 1 and 2).

The comparison for the flights at 100-foot cruising power shows that the lower power and tip speed of the four-bladed configuration provided somewhat quieter operation. This does not appear for flights under the same operating conditions at 500-foot altitude; however, the use of the 40-decibel weighting for these measurements would make the higher-frequency noise of the four-bladed propeller relatively more important. Use of the 40-decibel weighting gives results, for levels below 70 decibels, which compare more nearly with the loudness of the sounds, as heard by the ear, than measurements with flat weighting would provide. It is interesting to note, therefore, that the measurements indicate that the four-bladed configuration operating at a lower power and propeller tip speed than the Aeromatic would still sound as loud to the human ear as the Aeromatic configuration at a distance of several thousand feet.

The comparison for the flights at 500-foot maximum power is not consistent with the comparisons for the other flight conditions. Reference to the basic data for this operating condition shows that the records for the standard pusher with the Aeromatic propeller varied over a wide range when the airplane was approaching and was several thousand feet away. One of the records shows a nearly constant sound level at the microphone throughout the entire approach. It seems likely that abnormal refraction (see discussion of series A) was occurring for these measurements which made the average level during the approach considerably higher than it would normally have been. Comparison of the average curves for the four-bladed configuration, at 500-foot maximum power and 500-foot cruising power, shows that the curve for 500-foot maximum power fell below that for 500-foot cruising power during the approach. This again suggests abnormal refraction occurring, in this case in such a manner as to reduce the level during the approach for configuration 7 at 500-foot maximum power. It is probable that abnormal propagation conditions of this sort explain the inconsistently wide separation between the average curves for configurations 6 and 7 at 500-foot maximum power.

Ground analyses.- The ground analyses for the two- and four-bladed configurations of the standard pusher are shown in figure 43(c). Comparisons of the over-all level, engine fundamentals, and propeller fundamentals from these analyses are presented in figure 46. The analysis for configuration 6 shows the propeller noise generation to be most important at all but two of the measuring positions. For configuration 7, on the other hand, the engine fundamental is by far the largest component except at the two 150° positions. This difference between the two analyses is easily explained by the much lower power and speed for configuration 7 in the ground analysis.

The comparison of the over-all levels from the ground analyses (fig. 46) shows that the standard pusher with the Aeromatic propeller (configuration 6) was noisier than configuration 7 with the four-bladed propeller in the positions to the side and the rear where the high noise level of the propeller, for configuration 6, predominated. In the comparison of the engine fundamentals the nearly uniform radiation pattern for the unmuffled engine is clearly shown, and the engine fundamental for the engine operating at the lower speed for configuration 7 averages about 2 decibels higher than that for configuration 6.

The comparison of the propeller fundamentals shows the great increase in propeller noise generation with the increased tip speed and power of the Aeromatic configuration. It must be kept in mind, when comparing the results of the ground analyses in this series, that the analysis for configuration 6 has been plotted so that the outer circle of the polar plot corresponds to 120 decibels. The same scale has been used for the comparison of the over-all levels, but the other polar plots have been plotted so that the outer circle corresponds to 110 decibels.

Series F. Comparison of Standard and Modified Pushers with Standard and Modified Tractors

Flight measurements.- One of the important purposes of the present study was to compare the external noise generated by a representative pusher-type airplane with that of a conventional tractor-type airplane. The noise generation by tractor airplanes has previously been thoroughly investigated and theories have been developed which provide fairly accurate prediction of the noise level to be expected (see references 1 to 6, 8, and 10). In contrast with the work on tractor airplanes very little study has been made of the problem of noise generation by a pusher-type airplane on which the propeller rotates through air which has been disturbed by passage over the engine nacelle, hull, and wing surfaces. Series F presents a comparison of the noise generation in flights overhead at 500-foot altitude for the standard and modified tractor airplanes of reference 6 and the standard and modified pusher airplanes of the present report. Comparisons of the averaged curves for the standard tractor and the standard pusher at 500-foot maximum and cruising power are presented in figure 47. Comparison of the average of the curves for several of the modified configurations of the tractor (2A, 2B, 2F, 2C, and 2D) with a similar average of the curves for several of the modified pushers (9A, 9B, 9C, and 9D) is presented in figure 48.

These comparisons show a large difference in the way the sound level varied for flights overhead with the tractor and pusher airplanes. In the comparisons for the standard airplanes (fig. 47) the peak noise for the standard tractor is 8 to 10 decibels higher than the peak for the pusher, but the high noise level lasts for a much shorter time. Evidently the area in figure 47 under the curve for the tractor is much less than the area under the curve for the pusher. It is reasonable to suppose that the time integral of the noise level produced by an airplane would be related to a person's subjective estimate of the amount of noise it made. For this reason there is some basis for considering the standard pusher noisier than the standard tractor under the conditions for which it was measured, even though the peak level for the tractor is higher. This indicates the danger of comparing the noise generation by different airplanes simply in terms of the peak noise produced in a flight overhead.

The comparison of the averages of the modified tractors and pushers (fig. 48) shows clearly that the modified tractors were on the average much quieter than the modified pushers. The peak levels are very similar, but the high noise level of the tractor lasted for a much shorter time.

The difference in the shapes of the curves for the tractor and pusher, which is similar for all the measurements presented, can be explained by the differences between these two airplane types. First, as previously mentioned, the major noise sources on the pusher are shielded by the hull and wings of the airplane near the overhead position. It is this shielding that explains the dip in the pusher records occurring where the peak occurs in the tractor records. Second, there is evidently a difference in the directivity characteristics of the noise sources for the two airplane types. Shielding can explain the differences near the overhead position but cannot explain the increasing difference between the two airplane types at distances of several thousand feet. Further evidence of a difference in directivity may be found in the measurements from 3000 feet away in series G which show a difference in the shape of the sound-level variation when measured from the side. Shielding cannot be a major source of the difference under these conditions. It may be, of course, that the parts of the airplane which cause the shielding for the overhead flights are responsible for the evident differences in radiation characteristics for the noises of the two airplanes. A further reason for the difference in radiation characteristics is to be found in the difference in the character of the air flow into the propellers for the two airplanes. In the tractor the propeller turns through undisturbed air, while in the pusher the air flow into the propeller is disturbed by passage over the engine nacelle, hull, and wing surfaces. This disturbed air flow, in the case of the pusher, would be expected to interfere with the normal propeller noise generation since it introduces a nonuniformity in the air flow through the propeller disk.

Over-all levels from ground analyses.- Consideration of the radiation characteristics in flight for the pusher and tractor airplanes immediately raises the question of how the radiation characteristics shown by the over-all levels of the ground analyses compare. Figure 49 shows the over-all levels on the ground for both standard airplanes, and for the four-bladed geared and muffled configurations of both modified airplanes. The standard pusher appears to be as much as 10 decibels noisier without as large a difference in shape as might be expected from the results of the flight-measurement comparisons. The modified pusher (configuration 9B) is noisier than the modified tractor (configuration 2F) in many positions, and the shapes of the two curves are quite different. The modified pusher seems to have a more sharply directional radiation characteristic than the modified tractor, a result which is not in agreement with the results of the flight measurements. The air flow into the propeller when the engine is turning at 2500-rpm maximum power on the ground is different from the air flow into the propeller for the same power and speed in flight. Presumably, this difference in air flow for ground and flight measurements explains the differences in noise generation for these two measuring conditions.

It must be noted in studying the comparisons of this series that operating conditions for the two airplane types were somewhat different. Maximum power in flight corresponded to a higher power for the tractor than for the pusher. Furthermore, while the pusher measurements both on the ground and in flight were done at operating conditions which were always comparable with those for the standard pusher, this procedure was not employed in the measurements for the tractor. Reference to table II is necessary to determine the powers, tip speeds, and propeller diameters which must be taken into account in making comparisons.

Series G. Measurements from 3000 Feet Away for

Configurations 5, 6, 8, and 9B

In order to avoid the shielding effect of the hull and wings of the pusher, which evidently had a major effect on the sound levels measured for flights overhead, some measurements were made from a position 3000 feet from the nearest point of the flight path. It was also felt that these measurements might give a truer picture of the noise heard in the vicinity of an airport. The measurement technique presented various problems which made it seem less useful than had been expected, but some of the results were both unexpected and interesting.

Basic data.- The basic data showing the records of successive flights for the four configurations of this series at 500-foot maximum and cruising power, 3000 feet away, are presented in figures 50 and 51. As might be expected, these records show a large amount of fluctuation. The difficulties of this nature encountered with the measurements of overhead flights at distances greater than 3000 feet naturally occurred throughout the entire flight for the present measurements. This fluctuation makes the interpretation of the data more difficult but does not obscure the large difference between the sound levels measured for flights in opposite directions. This difference between the sound levels for flights north and flights south is apparent in varying degrees in all the measurements on the pusher configurations. No significant difference of this sort may be seen in the records for configuration 5 of the standard tractor. The maximum difference for the pusher configurations occurred when the airplane was about 2000 feet past the nearest point of the flight path. At this position a difference of about 10 decibels occurred for most of the records, with the noise radiated in the right rear quadrant of the airplane being louder than the noise radiated in the left rear quadrant. In attempting to determine a reason for this difference, consideration was given to the fact that the propeller rotates in a counterclockwise direction as seen from the rear of the airplane, which means that the maximum noise radiated horizontally comes from the side of the airplane on which the propeller blades are moving up. Consideration of the mechanism of noise generation would make it appear that the maximum noise should be radiated on the opposite side of this airplane where compression would be expected to occur each time a propeller tip approached the hull. This reasoning is evidently incorrect since the measurements consistently show that the maximum noise occurs on the side where the blades are moving away from the hull.

The records for the tractor airplane do not show a difference of this sort between the north and south flights but do show what appears to be a recurring reduction in the noise received from the airplane at the north end of its flight path. This difference might be a terrain difference, since there were some trees beneath a line from the airplane to the microphone at this end of the flight path. It seems surprising, however, that such a terrain difference was not noticed in the other measurements from 3000 feet away. Perhaps the large fluctuations in the records and the difference between the noise on the two sides of the pusher obscured this difference in the pusher records.

Comparative plots.- The basic data for each configuration in figures 50 and 51 have been averaged and presented in figure 52. The comparison for the flights at 500-foot maximum power clearly shows the large difference between the way the sound level varied for the flights of the standard tractor and the way it varied for the flights with the three different configurations of the pusher. The particularly high noise level of the tractor for these flights at maximum power was caused by operation at full throttle which provided 2800 rpm, 165 horsepower, and a propeller tip speed over 900 feet per second. This is a higher power than was used for the measurements of the standard tractor, configuration 1, presented in series F. Operation at this power provided a noise level sufficiently high so that the noise of the tractor could be measured throughout the 10,000-foot flight course. The pronounced directivity of the tractor noise may be seen when the variation in distance from airplane to microphone throughout the flight path is considered. At the nearest point the airplane is 3000 feet away, while at either end of the course, the airplane is less than 6000 feet away. This means that a source of sound which radiated uniformly in all directions should produce a sound level varying a maximum of 6 decibels as it moved from one end to the center of the flight course. The variation with the tractor over this distance was about 25 decibels showing that radiation near the plane of the propeller is about 20 decibels greater than that at a 60° angle in front of or behind the propeller plane. The tractor is evidently much more directive than the pusher, a result previously mentioned in the discussion of series F.

The standard tractor at cruising power made a peak noise about equal to that for the standard pusher, but the noise lasted for a much shorter time for the tractor. This result, similar to the result for the flights overhead, means that the standard tractor at cruising power is effectively a much quieter airplane than the standard pusher.

Measurements were not made from 3000 feet away on any of the modified tractors, because the airplanes were not available. If these airplanes are as much quieter than the standard tractor 3000 feet away as they were in the overhead measurements, then the modified tractors would be much quieter than the modified pushers.

An approximate sketch has been made of part of the directivity patterns in flight for the standard tractor and standard pusher airplanes. This polar plot (fig. 53) was derived from the records of figure 50 and correction has been made for variations in the distance of the airplane from the microphone which take into account the finite velocity of sound and the velocity of the airplane. The conventional inverse-square law of attenuation with distance has been used. It must be emphasized, however, that this graph should not be considered as representing the result of a thorough and careful measurement of the radiation pattern of the airplanes in flight but rather as a best estimate of this pattern available from the data of figure 50. For the sake of clarity a smoothed curve has been drawn through selected points. In addition to any errors introduced by drawing a smoothed curve the data are subject to the errors that were possible in the flight measurements. The sound-level scale used is a purely relative one using 0 decibels as the level occurring at the 90° position on the right for both airplanes. The sound levels for the two airplanes were found to be about alike at the 90° right position when the powers and tip speeds were nearly the same.

The difference between the directivities for the pusher and tractor is made strikingly clear by the polar plot of figure 53. The reasons for this difference are not entirely clear, but the measurements of series H offer one possible explanation. In the case of the pusher airplane, the harmonic components are believed to be equal to or greater in intensity than the fundamental and the directivity patterns for those components have their maximums at other than near -90°. The only analysis made of the noise spectrum for flight is discussed in the following section and it tends to confirm the above explanation. Further explanation will be found in the discussion of series H.

It is interesting to compare the measurements of the three configurations of the pusher from 3000 feet away with measurements for these configurations for the overhead flights. The data for 500-foot maximum power in series A (fig. 26) showed that the modified pusher (configuration 9B) averaged 8 to 10 decibels quieter than the standard pusher (configuration 6). The measurements from 3000 feet away show a difference of 6 to 8 decibels for these configurations which is not seriously different from the results of the overhead measurements. Comparison of configurations 6 and 8 in series B (fig. 34) also gave results similar to the comparison of these configurations from 3000 feet away.

Series H. Comparison of Analyses of Noise of Configuration 10 Flying on a Course Which Passed 3000 Feet Away with Ground Analyses Made 50 Feet from Propeller Hub

Some recordings were made on magnetic tape of the noise of the modified pusher, muffler relocated, with the eight-bladed propeller (configuration 10) from 3000 feet away. Time did not permit perfection of this new procedure or recordings of other configurations. Short samples of the recordings for two of the flights at 500-foot maximum power using flat weighting were analyzed. Calculations have been made showing the position of the airplane along its flight path when it generated the noise recorded on each of the samples analyzed. The position of the airplane has been expressed in terms of the distance from airplane to microphone and the angle measured between a line from the tail to the nose of the airplane and a line from the airplane to the microphone. In these calculations corrections have been made which include consideration of the velocity of the airplane and the finite velocity of sound so that the indicated direction is the direction in which the sound analyzed was radiated and the indicated distance is the actual distance that the sound traveled from airplane to microphone.

The flight analyses and ground analyses for comparable positions are presented in figure 54. The relationships between the various important frequency components are quite different for the two conditions.

In general, for the ground analyses of this series, only the first and second harmonics of the propeller tip-passage frequency were measurable above the background of nonharmonic noise, and the second harmonic was more than 10 decibels lower in amplitude than the fundamental. In addition, for the ground analyses, the engine fundamental was measurable and usually at a higher level than the propeller second harmonic. For the flight analyses, the engine fundamental was measurable at only one position, and the higher harmonics of the propeller, particularly the second and third, were sometimes nearly as important as the propeller fundamental. Harmonics as high as the sixth of the propeller frequency were measurable above the nonharmonic background. It is evident that noise at the propeller tip-passage frequency is the major noise for configuration 10 in flight. The importance of the higher harmonics of the propeller noise will be realized when it is considered that, because of the characteristics of the human ear, the noise of the higher harmonics would in many cases sound louder at the distances for which the measurements of this series were made than the noise at the fundamental frequency.

In addition to the difference between the character of the noise produced by the airplane in flight and on the ground, there is further evidence in the measurements of this series of a difference in the polar distribution of the over-all noise level around the airplane in flight and on the ground. The differences in over-all level between flight and ground measurements in similar directions are not what would be expected from a simple consideration of the theoretical inverse-square law of attenuation with distance. These results are also indicated by comparison of the data of series G (see particularly fig. 53) with the over-all levels from the ground analysis for the same configuration (see fig. 49).

No analyses are available at present of the noise of the tractor airplane in flight. Observers have reported that the modified tractors made much less of a whining noise in flight than the modified pushers. It is well-known that a whining noise is associated with intense higher-harmonic content. The measurements of reference 6 showed that for the modified configurations of the tractor using a six or eight-bladed geared propeller (2C and 2D) the flight noise at most measurement positions contained a large amount of nonharmonic vortex noise. It is likely that the noise of the pusher airplane because its propeller is turning through disturbed air contains both a larger relative amount of propeller noise and a higher level of the higher harmonics of the propeller noise relative to the fundamental than the noise of the tractor. If this difference in the character of the noise generated by the two airplane types does exist, it affords a possible explanation of the difference in the directivity of the noise as shown in series G (fig. 53). The directivity of the tractor noise should be determined primarily by the directivity of the vortex noise and the directivity of the predominant fundamental of the propeller noise. For the standard tractor of figure 53 the propeller fundamental is important and produces a directivity pattern resembling that calculated for the propeller fundamental from Gutin's theory (see fig. 1, reference 4). For the standard pusher, with the important second and third harmonics of the propeller noise, it is possible that the different directivity patterns for the different harmonics add up in such a way that their sum has the rather uniform over-all directivity shown in figure 53. The 40-decibel weighting used for figure 50, from which figure 53 was calculated, would increase the relative importance of the higher harmonics of the propeller noise.

Admittedly, the evidence for the above hypotheses which would explain the difference in directivity for the tractor- and pusher-type airplanes is sketchy. Evidence is drawn from scattered data on several different configurations. An explanation of this nature, however, seems likely to be correct in view of the available data.

It was mentioned in the discussion of precision that some trouble was experienced in the measurements for this series with variation of the sensitivity of the magnetic tape recorder. Possible errors arising from this difficulty must be taken into account in considering the over-all levels for the flight measurements. The relationships between the amplitudes of the various harmonic components in the flight analyses were probably not affected, however, so comparisons of the spectra for flight and ground measurements are subject only to the usual instrumental errors.

PERFORMANCE TESTS

In order to get some idea of the effect on performance of the various modifications made, take-off runs were made with the various configurations, and the distance required for the wheels to leave the ground was carefully measured. In order to eliminate, as much as possible, differences in piloting technique all take-offs were made in the same way by one pilot using a standardized procedure. Take-offs with the standard pusher were made with a full throttle setting throughout the take-off. Take-off procedure with the six experimental configurations using ground-adjustable propellers (8, 9A, 9B, 9C, 9D, and 10) was similar to that used for the sound-measurement take-offs. This involved reducing the throttle setting during the take-off so that the engine speed did not exceed 2600 rpm. The propeller pitch was set for these performance tests as it was for the ground analysis and take-off measurements, so that the maximum speed at the start of the take-off would be 2500 rpm. This procedure provided the experimental configurations with a slightly higher power for the start of the take-off but with a reduction in power during take-off. It was felt that this procedure gave a reasonable approximation to the performance of a constant-speed propeller. This procedure was, of course, impossible for the solid four-bladed propeller of configuration 7. In this case take-offs were made with a full throttle setting, but the lower speed and power during the take-off provided relatively poor performance.

Table III presents the results of these performance tests. The take-off distances indicated in the table are the averages of the four best runs in a series of approximately eight take-offs for each configuration. The greater weight of the experimental configurations is simply that due to the gearing, muffler, and propellers. With these weights the take-off distance averages about 10 percent greater for the experimental configurations that were operated under fairly comparable conditions.

Maximum airspeeds in level flight are presented in table III as an additional indication of performance. The propellers of the experimental configurations were set for these tests so that they all absorbed approximately the same level-flight power as that of the standard propeller. It must be noted in considering these speeds that they were read from two different uncalibrated meters, one used for configurations 6 and 7 and the second, for the other six configurations. This probably means that the small differences observed are insignificant.

GENERAL DISCUSSION

A study of the data presented in series A to H shows that several important conclusions can be drawn. In addition, it is evident that some questions have been raised which remain unanswered. The most general conclusion from the data of the present report is that noise generation by the pusher-type airplane does not follow the theories which have been found to apply to noise generation by tractor-type airplanes. As suggested in the discussions of series E and F this result is not surprising since the air flow into the propeller of a pusher-type airplane is disturbed by passage over the engine nacelle, hull, and wing surfaces. The theory of propeller noise generation, which has been useful for tractor-type airplanes, assumes a uniform flow of undisturbed air into the propeller.

One result of this interference with the normal flow of air in the pusher configuration is that the pusher airplane, operating at a lower engine power and propeller tip speed than the tractor-type airplane, radiates a larger amount of noise energy. The comparison of series G showed that at cruising power the standard pusher and tractor made comparable peak noise levels in a flight passing 3000 feet away. The noise of the pusher, however, remained at a high level throughout 10,000 feet of flight, whereas the noise produced by the tractor dropped off rapidly as the airplane flew away. For the modified configurations of the pusher the noise was reduced by the lower tip speed of the propellers and, for many conditions, was further reduced by the use of engine exhaust muffling. This reduction through lower tip speed and mufflers which amounted to from 7 to 10 decibels is of about the same magnitude as that obtained by similar modifications of the tractor-type airplane.

A difference in the noise generation by the tractor and pusher airplanes, which is probably also explained by the disturbed air flow into the pusher propeller, may be seen in the data for series A which show the effect of increasing the number of propeller blades. For the geared and muffled pusher airplane increasing the number of propeller blades beyond four tended to increase the noise generation over that with a four-bladed propeller. With a tractor-type airplane such as the one tested both theory and experience indicate a significant reduction in noise level with an increase of the number of propeller blades from four to six or eight (see reference 6).

It is likely that, with the geared engine used in this study, a simpler muffler and a three-bladed propeller on the pusher airplane would provide as quiet operation as possible at the propeller tip speeds used. Since the reduction in propeller tip speed from the standard to the modified configurations is the major source of the reduction in noise level, it is likely that a further reduction in the tip speed with a greater gear-reduction ratio would produce still more reduction in the noise generation. If this change were made, it might be desirable to use a muffler as effective as the one used in the present study, in order to take full advantage of the reduction in propeller noise.

When comparing the noise generated by the pusher airplane with the noise generated by conventional tractor-type airplanes, the nonharmonic vortex noise generation must be considered as well as the harmonic noise at multiples of the propeller and engine frequencies. In measurements for the tractor airplane tested, and other tractor-type airplanes, vortex noise generation has meant that the reduction in noise level with an increase of the number of blades was not so great as would be expected if the tip-passage noise was considered alone. In general, vortex noise has provided a limit to the noise reduction obtainable by using multi-bladed propellers turning at reduced speeds. This raises the question of where vortex noise generation begins to limit the reduction in noise obtainable with the pusher-type airplane. The ground analyses for configurations 9A, 9B, 9C, and 9D show that a nonharmonic noise which appears to be an exaggerated vortex noise did increase in importance with an increase in the number of propeller blades. From the ground analysis it appeared that this vortex noise was at least partly responsible for the lack of pronounced change in the over-all level with increasing numbers of blades. The analysis on the ground for configuration 10, with the exhaust not passing through the propeller, showed a reduction in vortex noise, accompanied by some increase in propeller noise, over that for the comparable configuration (9D) with the exhaust passing through the propeller. This result suggested that the exhaust passing through the propeller was involved in both the lower tip-passage noise and the higher vortex noise for configuration 9D.

An analysis was made of the noise in flight of configuration 10 (series H) which showed a great predominance of harmonic noise occurring at multiples of the propeller tip-passage frequency. No analyses were made of the noise of configuration 9D in flight, but observers on the ground reported that its noise in flight was similar to the noise for configuration 10. This probably means that the noise generated by the geared pusher in flight did not contain the high level of vortex noise noticed in the ground analysis. This again implies that a further reduction in propeller tip speed would be useful in reducing the over-all propeller noise generation.

Such a conclusion seems to be in conflict with the results of the ground analyses, but the question is immediately raised whether the noise measured in the ground analyses is fairly comparable with the noise generated in flight. The data of series H show that, at least in some cases, the noise of the airplane running on the ground is quite different from the noise generated in flight. Other evidence was found throughout the measurements for this report that the results of ground analyses were not consistent with flight measurements. It is not completely clear from the evidence available why this should be true.

The preceding discussion has shown evidence that the noise of the modified configurations of the pusher airplane in flight is largely made up of harmonic components of the propeller tip-passage frequency. A flight analysis showed that this was true for configuration 10, and it seems likely that a predominance of propeller tip-passage noise also occurred for configurations 9A to 9D in flight. This annoying harmonic whine of the geared and muffled pushers is in marked contrast with the noise of the geared and muffled tractor airplane, especially for the higher number of propeller blades. Although no analyses have been made of the noise in flight of the modified tractors, there is both theoretical and practical evidence that nonharmonic vortex noise is an important component of the noise of these airplanes. Observers who have heard both the modified tractors and the modified pushers have commented on the marked difference in the character of the noise of the two airplane types as well as on the difference in the amount of noise made. Evidence of this sort supports the hypothesis of series H about the difference in directivity of the pusher- and tractor-type airplanes. Practical experience with complaints from people living near the airport from which both of these airplanes were flown has indicated that, while very few complaints were received about the noise of the tractor configurations, violent objections were raised about the noise of repeated flights over the test course for the pusher configurations. This difference is probably attributable both to the difference in the duration of the noise for the two types of airplanes and to the difference in the character of their noise. It is likely that even at the same noise level the swish of the modified tractors would be less annoying than the whine of the modified pushers. There are not at present any measures of annoyance available to check this hypothesis.

Another important problem which must be considered in studying the effectiveness of modifications designed to reduce noise generation is the effect these modifications have on performance. The take-off distances and airspeeds at maximum power of table III show that performance is not seriously affected by the modifications. It must be remembered that these figures were measured with the propeller pitch for the experimental configurations set differently for take-offs and for flight. These propellers, in effect, were treated as variable-pitch propellers for the performance comparisons. A fixed-pitch propeller cannot provide both the short take-off run and high top speed of a variable-pitch propeller. If a propeller using more than two blades must be used with a geared engine, the cost of providing variable pitch for this multibladed propeller must be considered.

The problem of quieting the pusher-type airplane is thus a complex one. Pusher-type propellers turning through disturbed air evidently are sources of more noise than tractor-type propellers for the same operating conditions. Reduction of propeller tip speeds in conjunction with some exhaust muffling seems to be the only solution to the noise problem for pushers. The same general conclusion also applies, of course, to tractors, but a greater reduction in tip speed is necessary with pushers to achieve the same effective noise output. It is thus easier to quiet tractors than pushers.

CONCLUSIONS

The following conclusions apply to the external noise level and the performance of a three-place pusher-type amphibian airplane:

1. It is possible to achieve a 7- to 10-decibel reduction of external noise by the use of slow-turning propellers in conjunction with engine exhaust mufflers.

2. Increase in the number of propeller blades above four on the geared and muffled airplane does not produce significant changes in the external noise level.

3. A muffler exhausting through the propeller under the conditions of the present study does not increase the over-all noise generation.

4. The noise level is not reduced under most conditions by the use of a smaller-diameter, four-bladed propeller at the same power without gear reduction and engine muffling.

5. The sound radiation from an airplane operating on the ground appears to be quite different from the radiation in flight, both as to directivity and harmonic composition.

6. The pusher-type airplane in both the standard and modified configurations radiates sound more uniformly in all directions in flight than do the tractor-type airplanes. While the maximum noise level in a flight overhead or passing 3000 feet away is about the same for the two types, the lack of sharp directivity in the pusher means that the noise level for the pusher remains high for a longer time.

7. In addition to the difference in duration of the noise produced by the tractors and pushers, there is also a difference in the character of the noise which may make the pusher noise still more objectionable.

8. Performance of the pusher airplane evidently would not be seriously reduced by the use of a geared engine and an exhaust muffler provided a variable-pitch propeller were used.

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2. Theodorsen, Theodore, and Regier, Arthur A.: The Problem of Noise Reduction with Reference to Light Airplanes. NACA TN 1145, 1946.

3. Hicks, Chester W., and Hubbard, Harvey H.: Comparison of Sound Emission from Two-Blade, Four-Blade, and Seven-Blade Propellers. NACA TN 1354, 1947.

4. Hubbard, Harvey H., and Regier, Arthur A.: Propeller-Loudness Charts for Light Airplanes. NACA TN 1358, 1947.

5. Regier, Arthur A., and Hubbard, Harvey H.: Factors Affecting the Design of Quiet Propellers. NACA RM L7H05, 1947.

6. Beranek, Leo L., Elwell, Fred S., Roberts, John P., and Taylor, C. Fayette: Experiments in External Noise Reduction of Light Airplanes. NACA TN 2079, 1950.

7. Regier, Arthur A.: Effect of Distance on Airplane Noise. NACA TN 1353, 1947.

8. Stowell, E. Z., and Deming, A. F.: Vortex Noise from Rotating Cylindrical Rods. NACA TN 519, 1935.

9. Davis, Don D., and Czarnecki, K. R.: Dynamometer-Stand Investigation of a Group of Mufflers. NACA TN 1838, 1949.

10. Hubbard, Harvey H., and Regier, Arthur A.: Free-Space Oscillating Pressures near the Tips of Rotating Propellers. NACA Rep. 996, 1950.

TABLE I.- AIRPLANE CONFIGURATIONS REFERRED TO IN REPORT

Configuration	Airplane	Illustrated in –	Engine	Muffler	Propeller					
					Number of blades	Type of blade	Diameter (in.)	Hub adapter	Pitch setting at 3/4 station (deg)	
1	Standard tractor	Reference 1	Direct-drive	None	2	Skyblade	76	None	18.5 (fixed)	
2A	Modified tractor	Reference 1	Geared	2	2	Wide	84.5	Eight-bladed	21	
2B	Modified tractor	Reference 1	Geared	2	3	Medium	76	Six-bladed	23.5	
2F	Modified tractor	Reference 1	Geared	2	4	Medium	76	Eight-bladed	22	
2C	Modified tractor	Reference 1	Geared	2	6	Thin	76	Six-bladed	21	
2D	Modified tractor	Reference 1	Geared	2	8	Thin	76	Eight-bladed	18.5	
5	Standard tractor	Reference 1 and fig. 6	Direct-drive	None	2	Wooden	76	None	14 (fixed)	
6	Standard pusher	Figure 1	Direct-drive	None	2	Aeromatic	78	None	11.5 to 23	
7	Standard pusher	Figure 7	Direct-drive	None	4	Solid	68	None	15.5 (fixed)	
									2500 rpm on ground	2500 rpm in air
8	Modified pusher	Figure 3	Geared	None	4	Medium	78	Eight-bladed	21	27
9A	Modified pusher	Figures 2 and 8	Geared	[a]1	3	Medium	78	Six-bladed	23.5	28.3
9B	Modified pusher	Figure 8	Geared	[a]1	4	Medium	78	Eight-bladed	21	27
9C	Modified pusher	Figure 8	Geared	[a]1	6	Thin	78	Six-bladed	22	27
9D	Modified pusher	Figure 8	Geared	[a]1	8	Thin	78	Eight-bladed	18.5	24.5
10	Modified pusher	Figure 4	Geared	[b]1	8	Thin	78	Eight-bladed	18.5	24.5

[a]Exhausting through propeller.

[b]Relocated.

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TABLE II.- PROPELLER TIP SPEEDS AND ESTIMATED ENGINE POWERS[1]

Airplane	Configu-ration	Propeller			Ground tests			Flight tests					
								Maximum power			Cruising power		
		Number of blades	Diameter (in.)	Ratio of propeller speed to engine speed	Engine speed (rpm)	Engine power (hp)	Propeller tip speed (ft/sec)	Engine speed (rpm)	Engine power (hp)	Propeller tip speed (ft/sec)	Engine speed (rpm)	Engine power (hp)	Propeller tip speed (ft/sec)
Standard tractor	1	2	76	1.00	1940	95	646	2600	155	862	2350	115	779
Modified tractor	2A	2	84.5	.632	2600	155	603	3100	185	720	2600	110	603
Modified tractor	2B	3	76	.632	2740	165	572	3050	180	638	2600	110	544
Modified tractor	2F	4	76	.632	2640	155	552	3100	185	645	2675	115	558
Modified tractor	2C	6	76	.632	2720	160	568	3100	185	645	2600	110	544
Modified tractor	2D	8	76	.632	2700	160	564	3000	180	627	2625	120	548
Standard tractor	5	2	76	1.00				2800	165	928	2450	110	812
Standard pusher	6	2	78	1.00	2500	140	850	2600	145	885	2450	120	833
Standard pusher	7	4	68	1.00	2125	115	630	2750	145	815	2450	105	726
Modified pusher, unmuffled	8	4	78	.632	1900 2500	90 145	408 537	2500	140	537	2250	95	483
Modified pusher, muffled	9A	3	78	.632	2500	145	537	2500	140	537	2250	105	483
Modified pusher, muffled	9B	4	78	.632	1900 2475	90 40	408 532	2500	145	537	2250	110	483
Modified pusher, muffled	9C	6	78	.632	2500	145	537	2500	145	537	2250	105	483
Modified pusher, muffled	9D	8	78	.632	2500	145	537	2500	140	537	2250	100	483
Modified pusher, muffler relocated	10	8	78	.632	2500	145	537	2500	140	537	2250	105	483

[1]Powers given to nearest 5 hp.

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TABLE III.- PERFORMANCE

[Take-off run and top speeds]

Airplane	Configu-ration	Approximate over-all weight (lb)	Maximum power[1] in level flight (hp)	Maximum level-flight indicated airspeed (mph)	Take-off run (ft)		
					Average	Maximum	Minimum
Standard pusher	6	1898	145	126	499	504	495
Standard pusher with solid four-bladed propeller	7	1892	145	125	779	785	773
Modified pusher, unmuffled	8	1995	145	124	565	573	559
Modified pusher, muffled	9A	2005	140	125	554	556	552
Modified pusher, muffled	9B	2012	145	123	569	572	565
Modified pusher, muffled	9C	2014	145	124	560	564	555
Modified pusher, muffled	9D	2022	140	123	533	535	530
Modified pusher, muffler relocated	10	2028	145	125	566	560	571

[1]Powers given to nearest 5 hp.

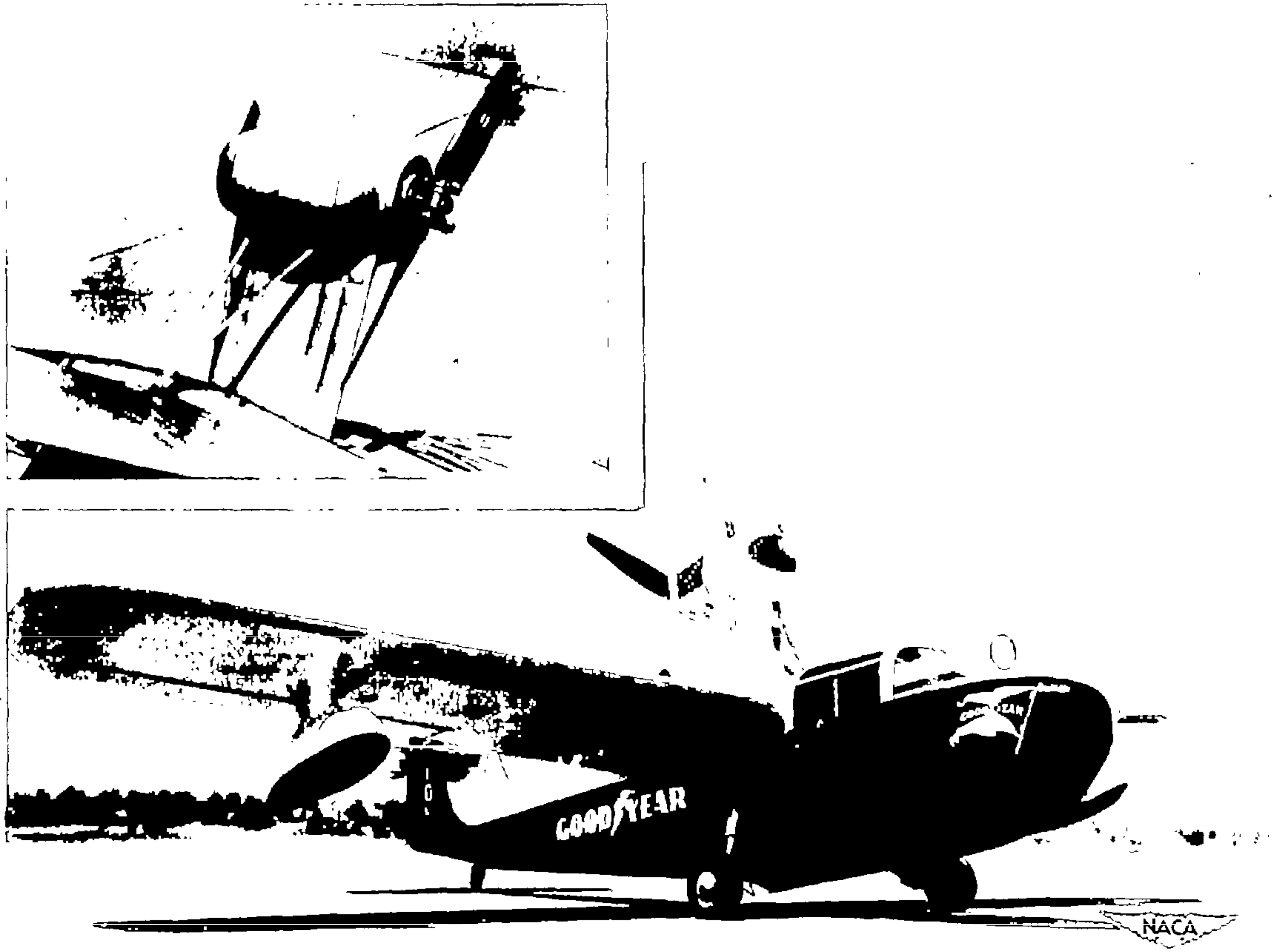
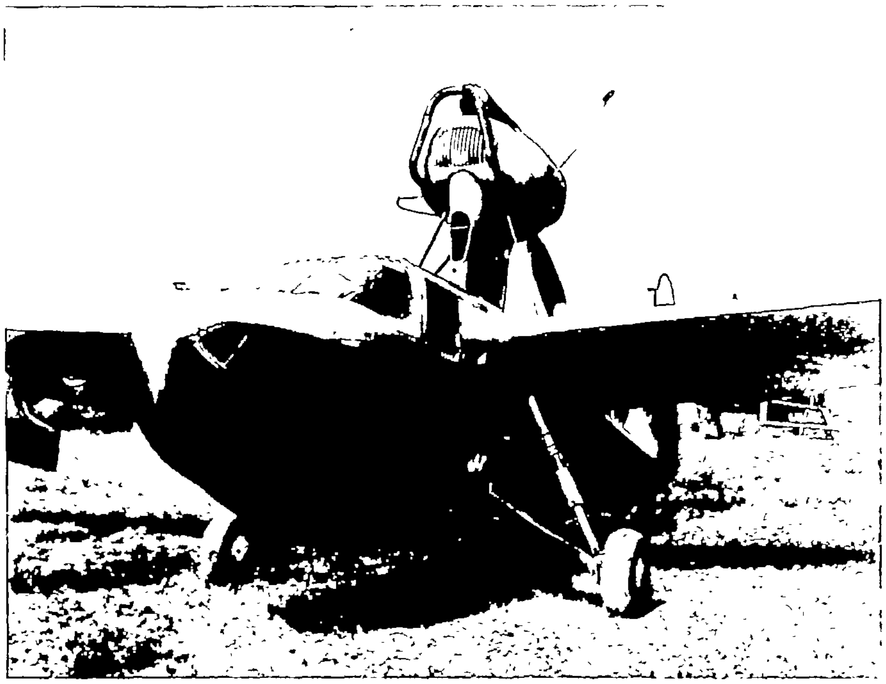


Figure 1.- Standard pusher with Aeromatic propeller, configuration 6.



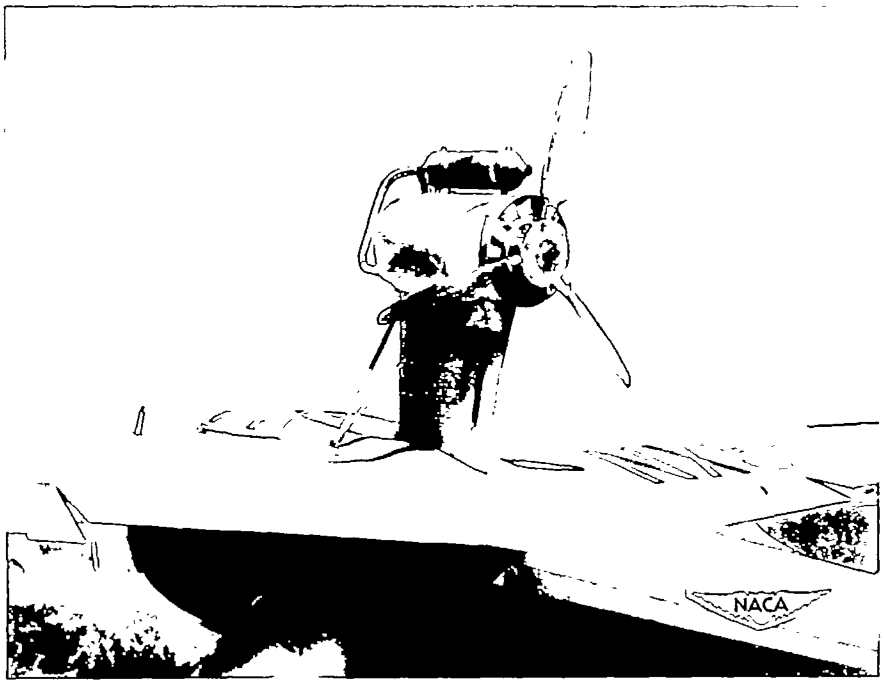


Figure 2.- Modified pusher with geared engine, muffler, and three-bladed propeller, configuration 9A.

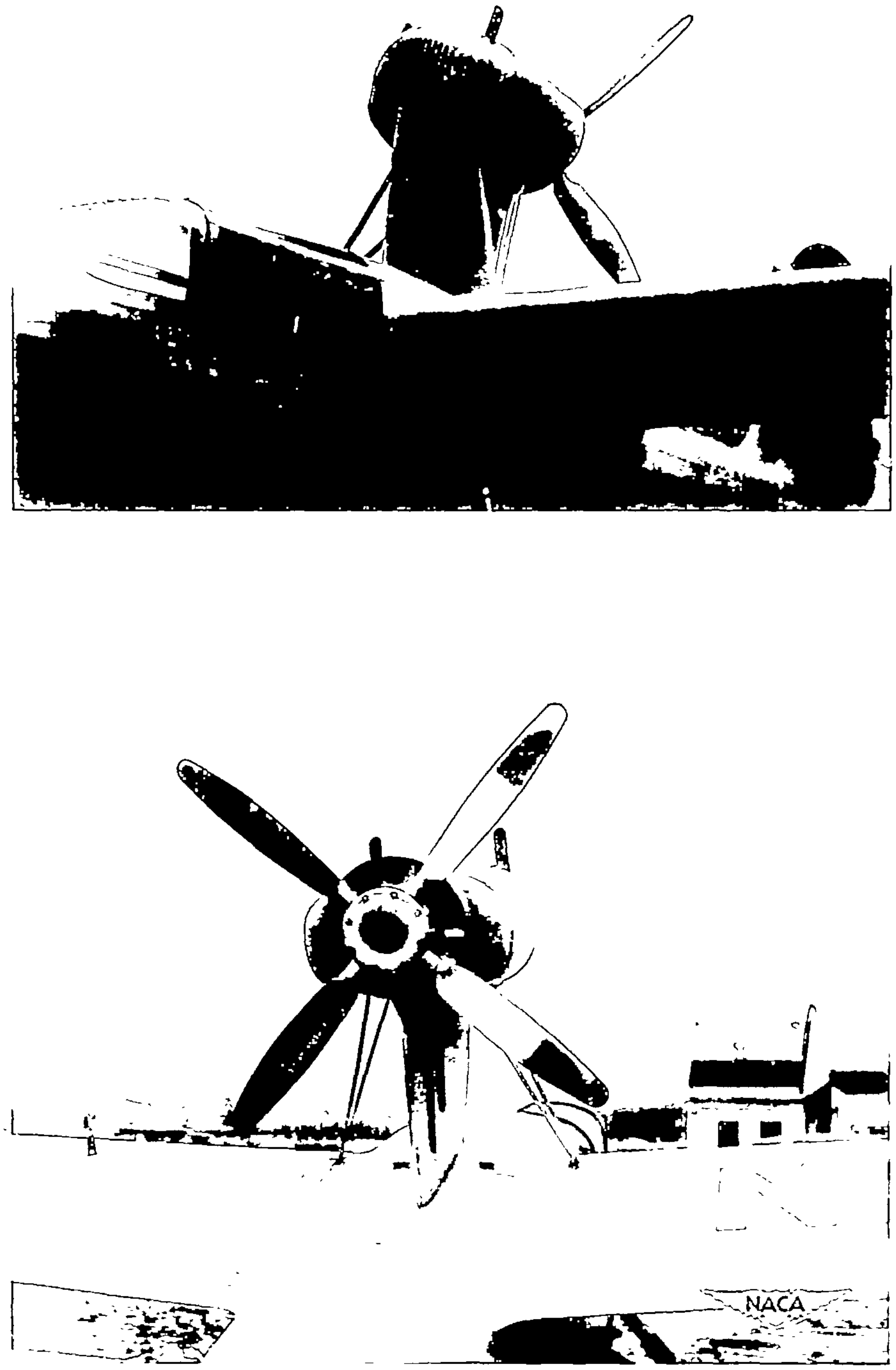


Figure 3.- Modified pusher, unmuffled, with four-bladed propeller, configuration 8.

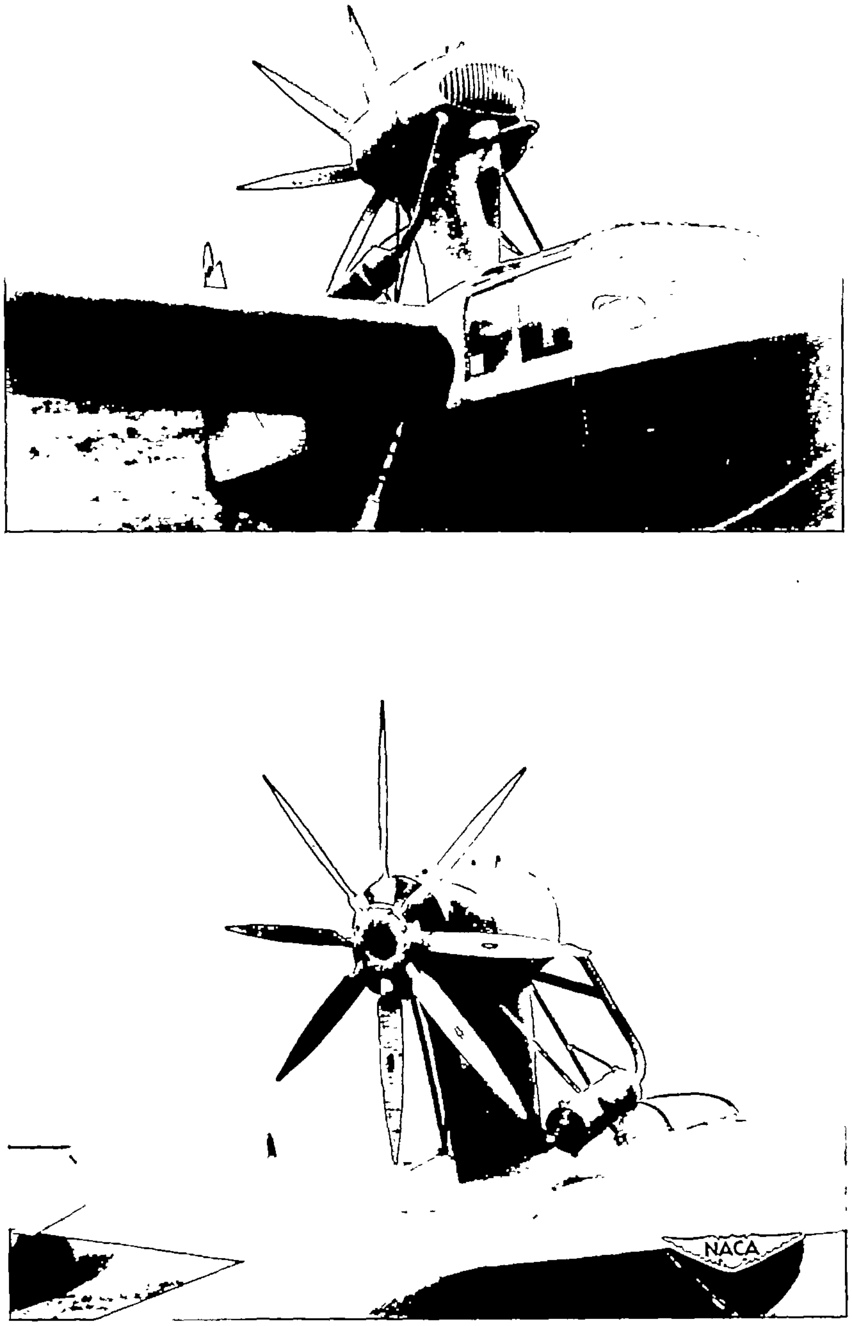


Figure 4.- Modified pusher, muffler relocated, with eight-bladed propeller, configuration 10.

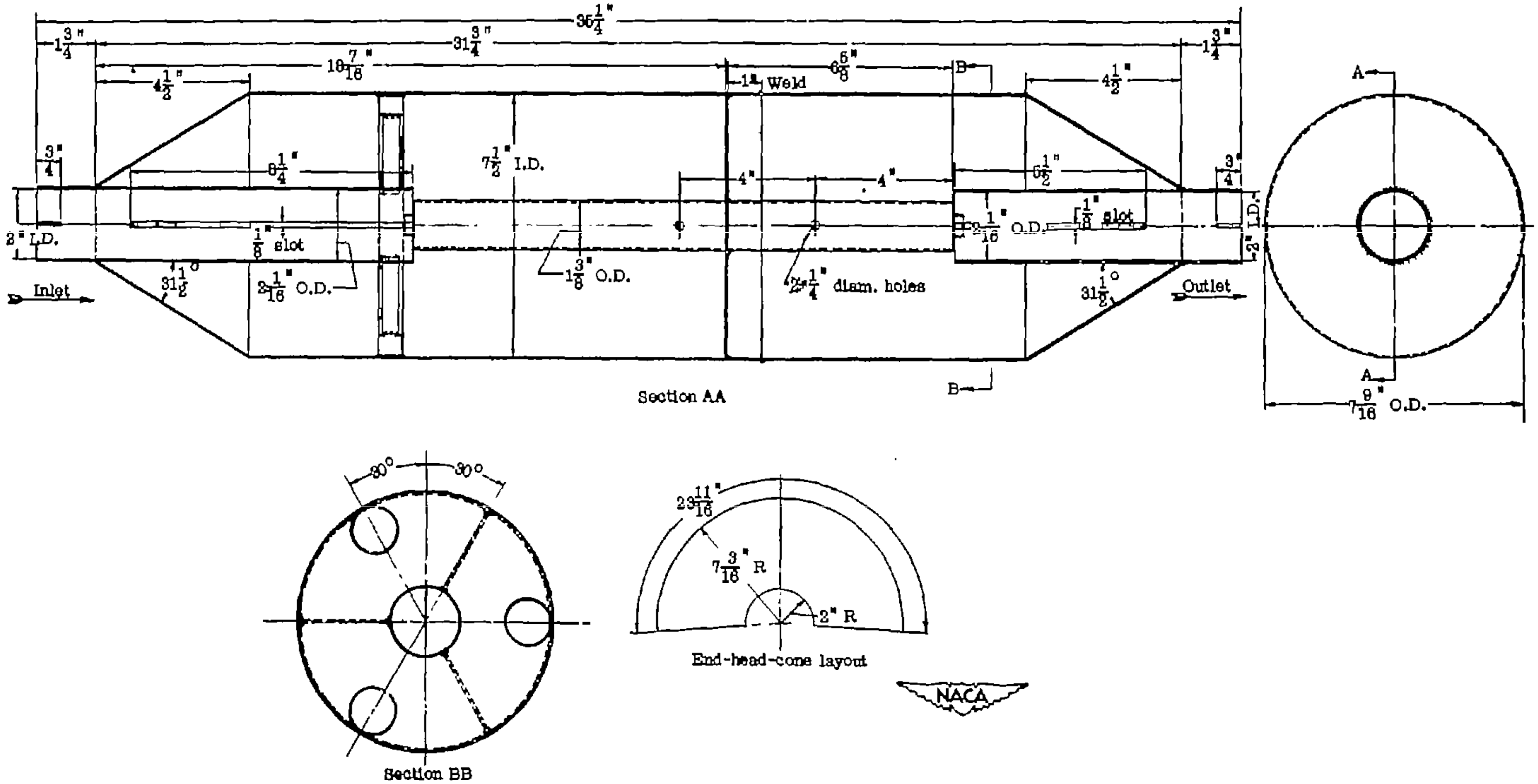


Figure 5.- Cross-sectional drawing of Maxim silencer.

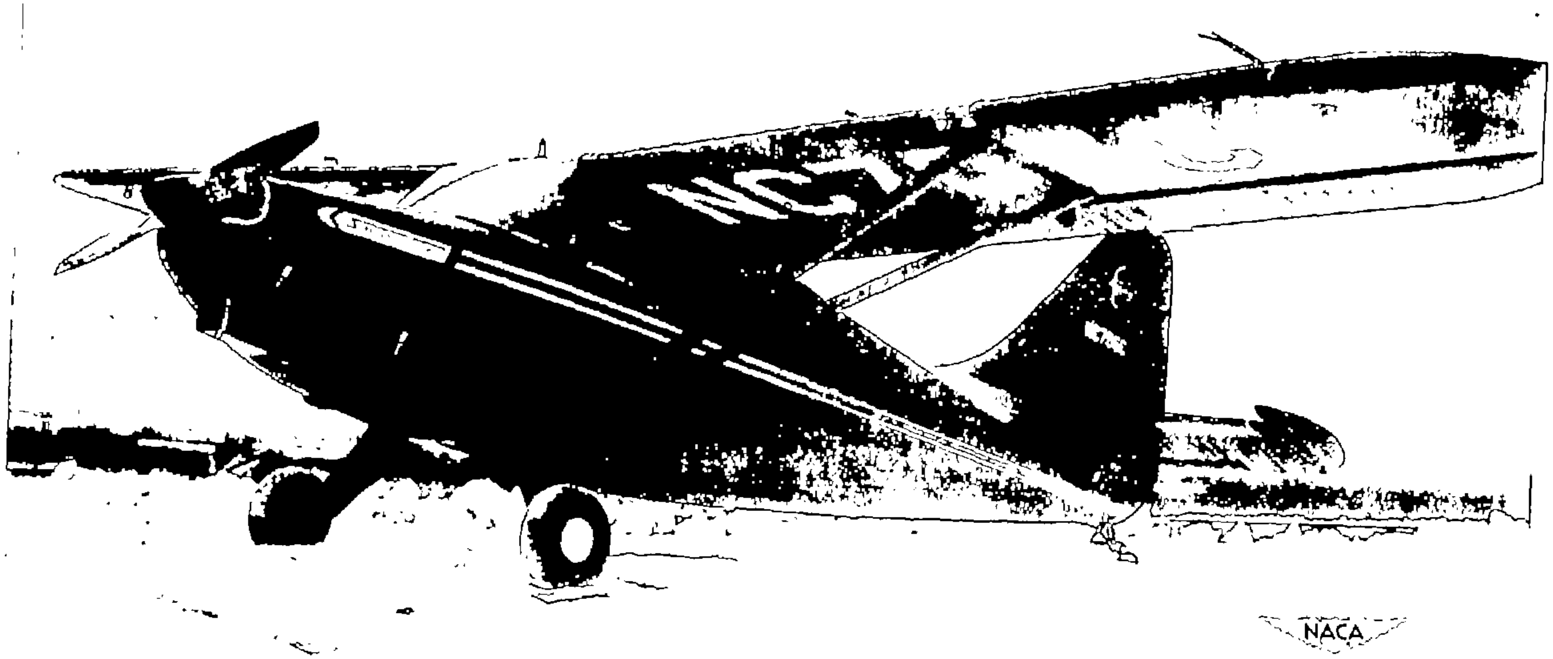
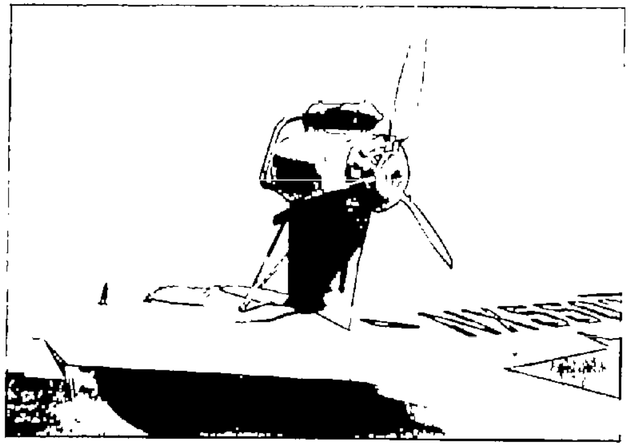
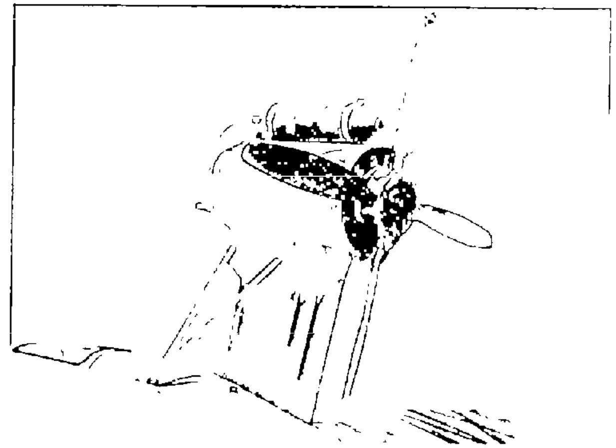


Figure 6.- Standard tractor, configuration 5.

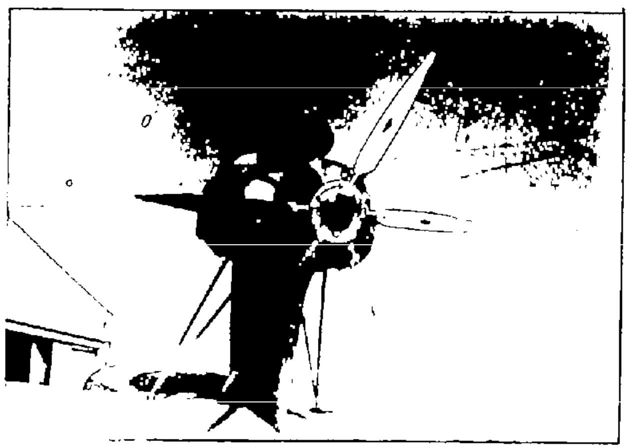
Figure 7.- Standard pusher with solid four-bladed propeller, configuration 7.



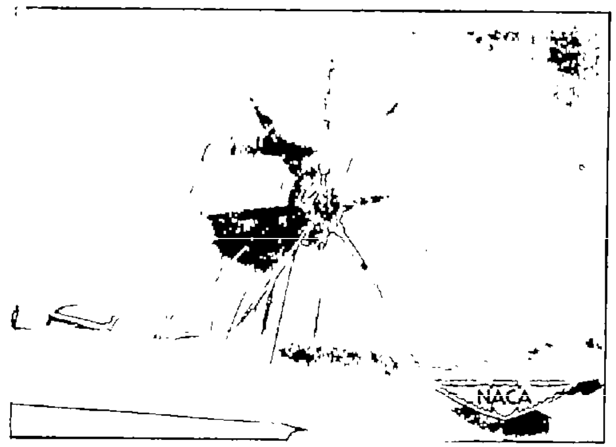
(a) Three-bladed propeller, configuration 9A.



(b) Four-bladed propeller, configuration 9B.



(c) Six-bladed propeller, configuration 9C.



(d) Eight-bladed propeller, configuration 9D.

Figure 8.- Modified pusher with various propellers.

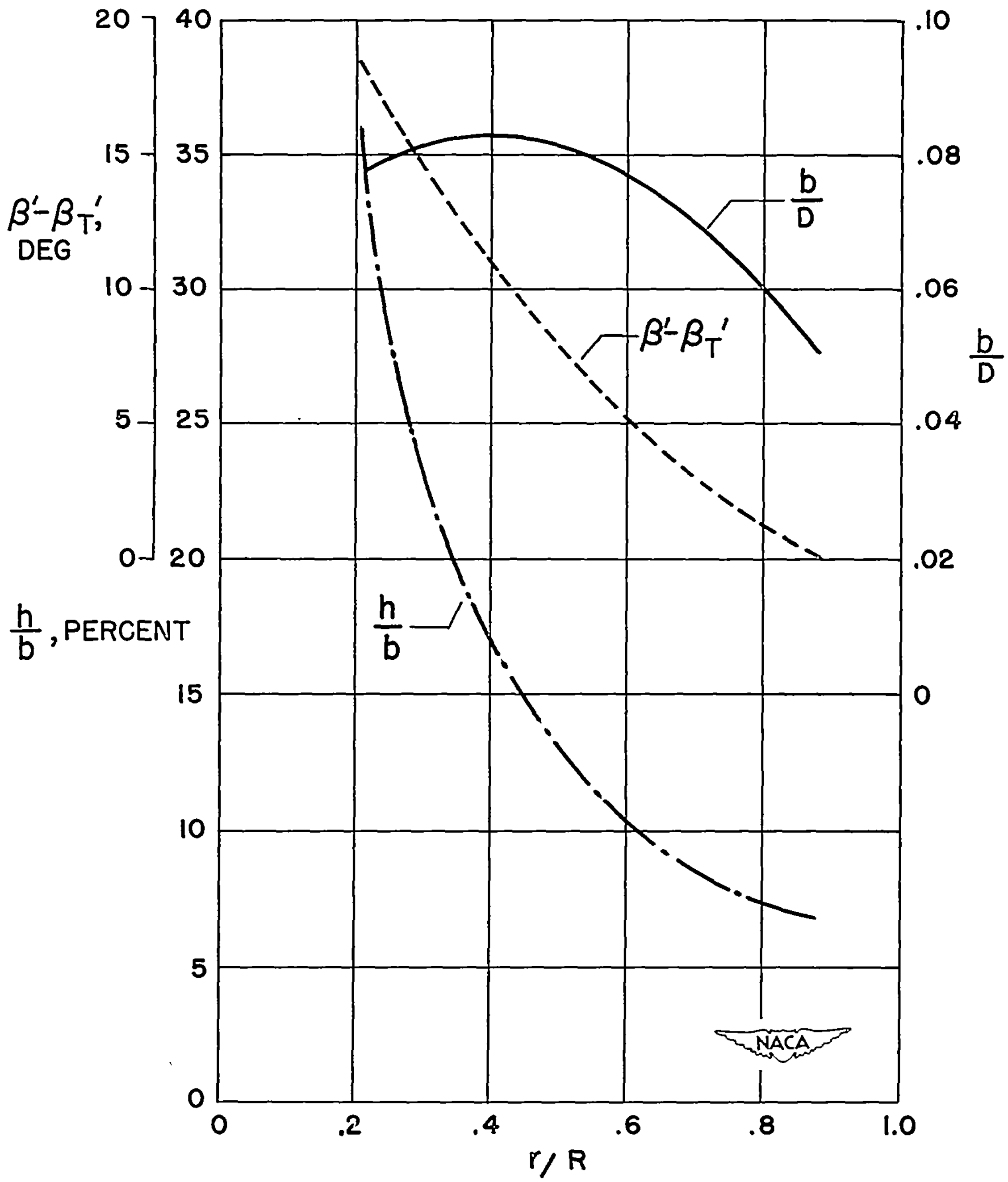


Figure 9.- Blade-form curves for Aeromatic propeller (see table I). D, diameter of propeller; R, tip radius; r, radius of element; b, width (chord) of element; h, maximum thickness of element; β', pitch angle of element; β_T', pitch angle of tip element.

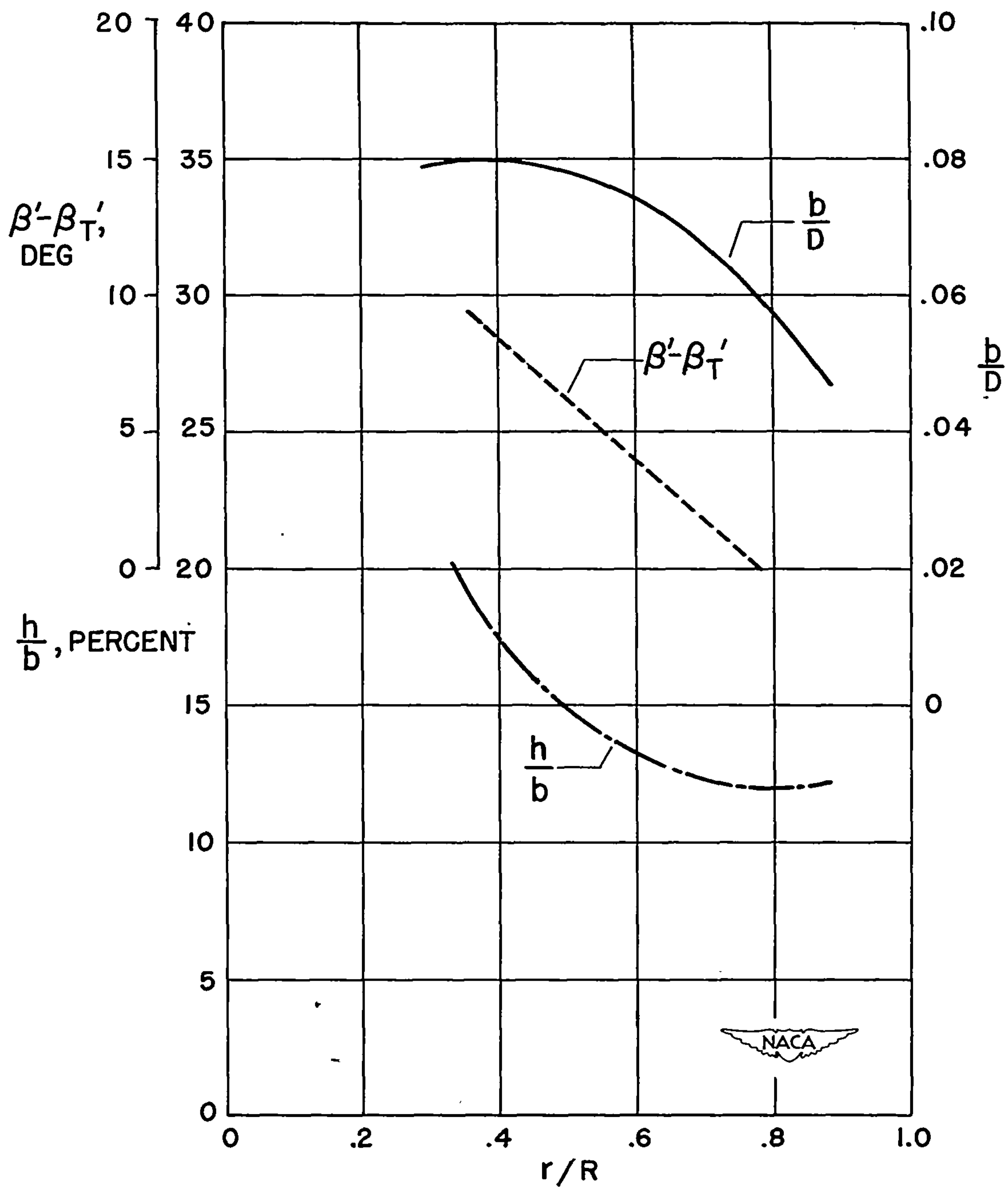


Figure 10.- Blade-form curves for fixed-pitch, solid, four-bladed propeller (see table I). D, diameter of propeller; R, tip radius; r, radius of element; b, width (chord) of element; h, maximum thickness of element; β', pitch angle of element; β_T', pitch angle of tip element.

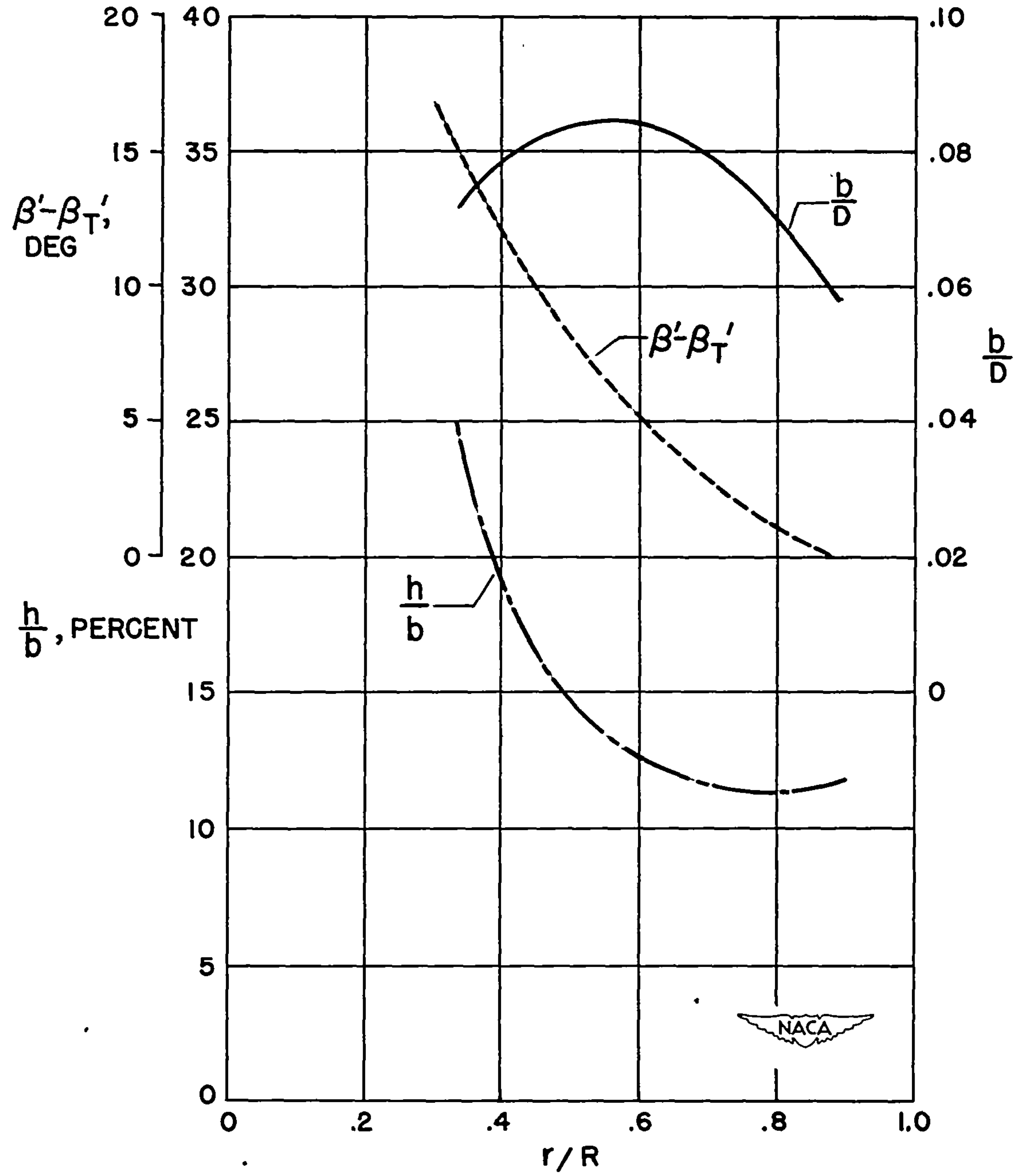


Figure 11.- Blade-form curves for medium-bladed propeller (see table I). D, diameter of propeller; R, tip radius; r, radius of element; b, width (chord) of element; h, maximum thickness of element; β', pitch angle of element; β_T', pitch angle of tip element.

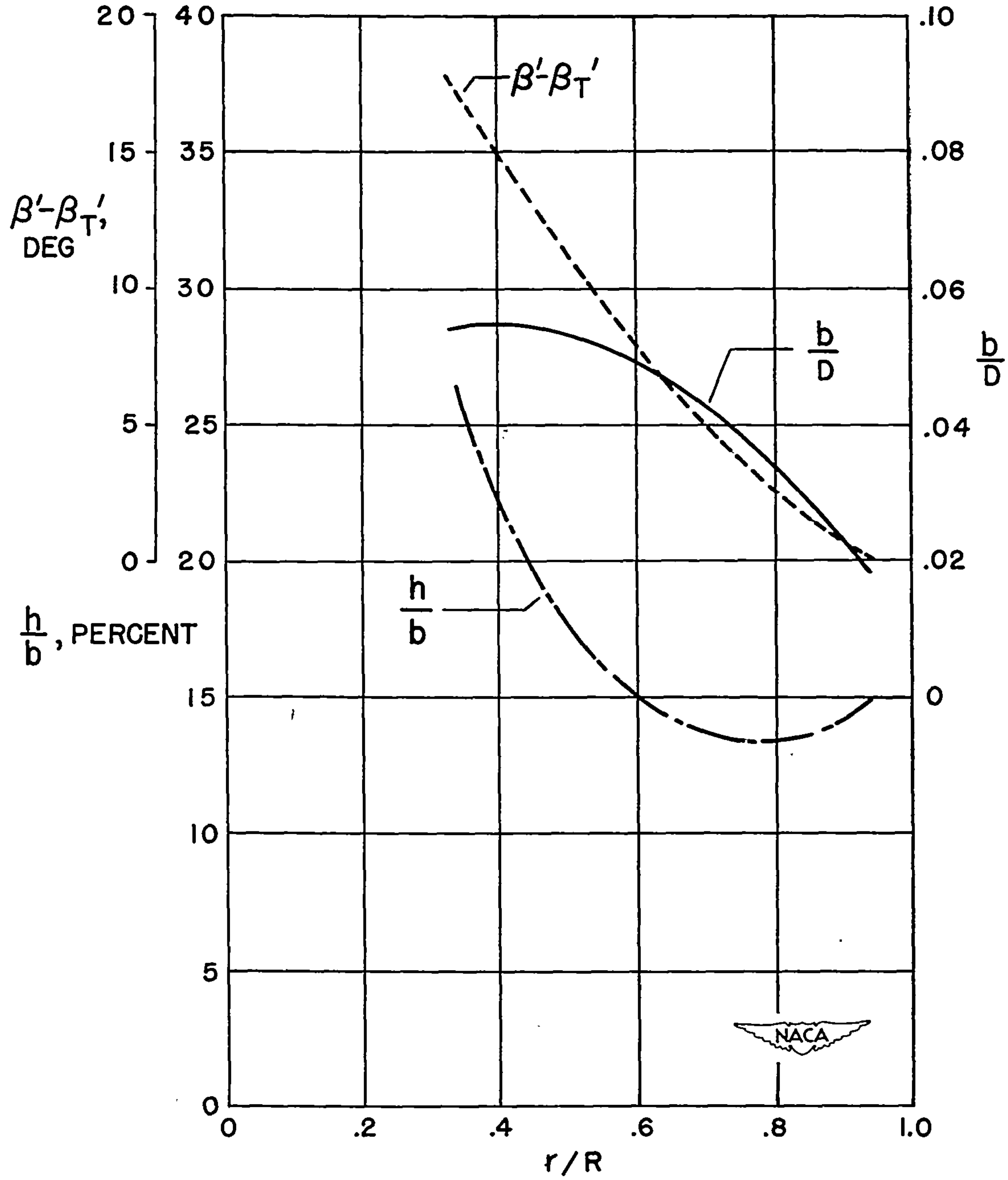
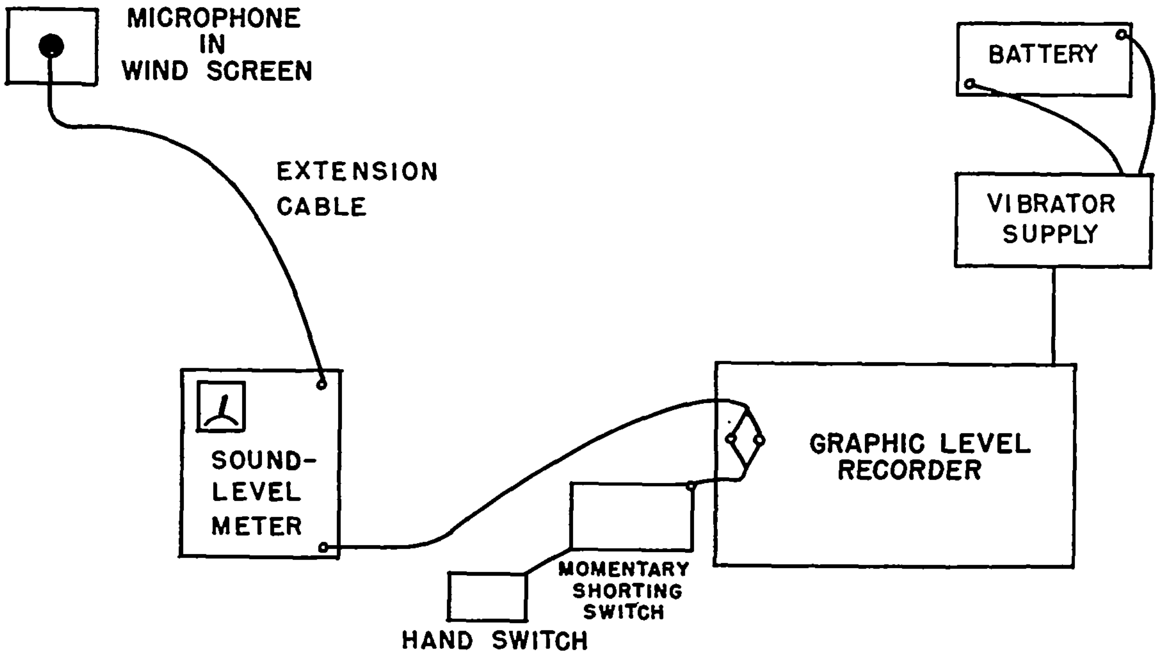
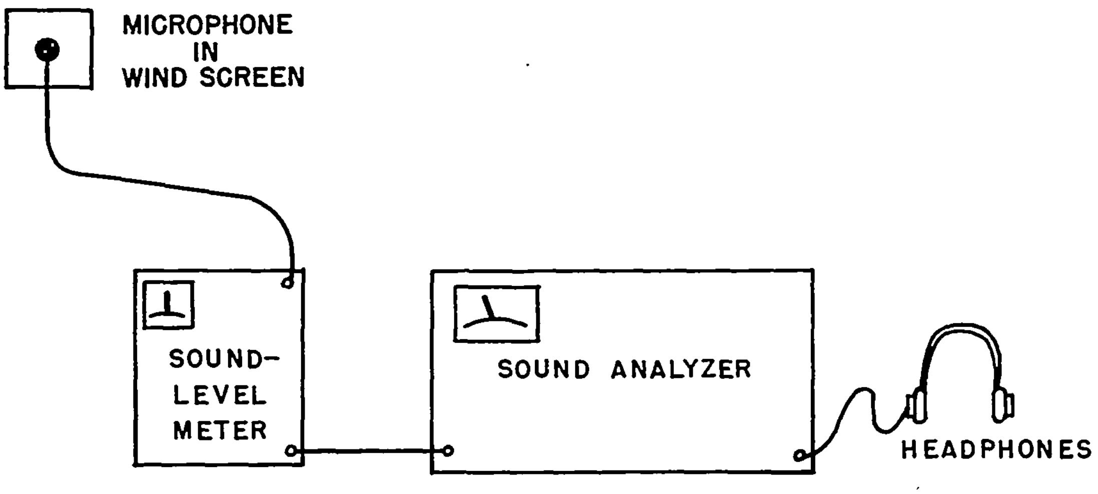


Figure 12.- Blade-form curves for thin-bladed propeller (see table I). D, diameter of propeller; R, tip radius; r, radius of element; b, width (chord) of element; h, maximum thickness of element; β', pitch angle of element; β_T', pitch angle of tip element.



(a) For flight and take-off measurements.



(b) For ground analysis.

Figure 13.- Equipment interconnections.

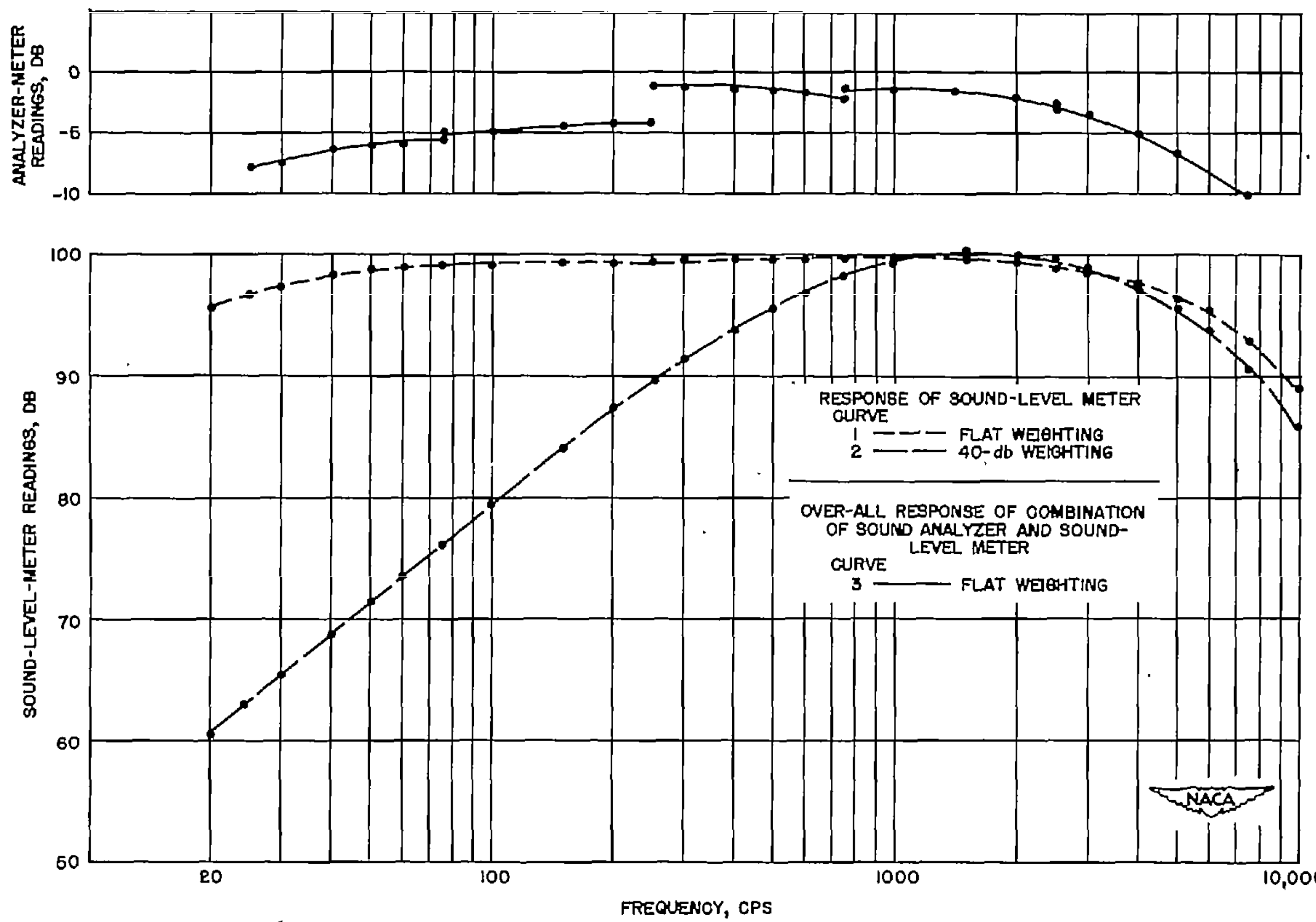
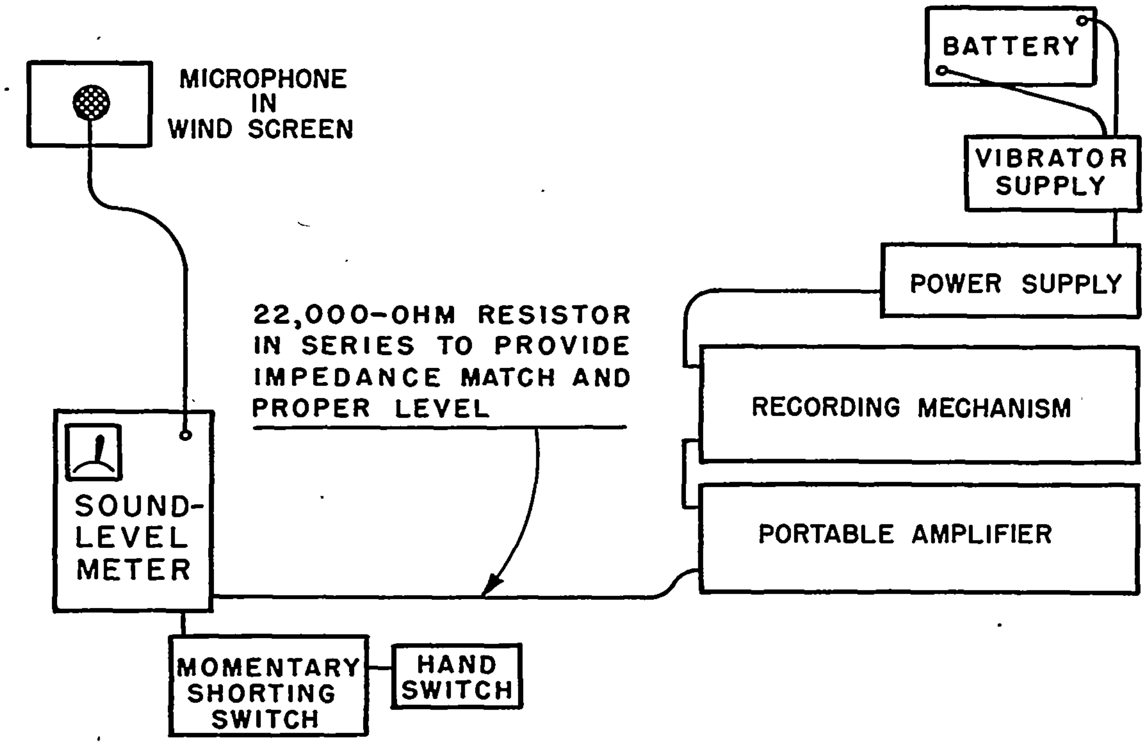
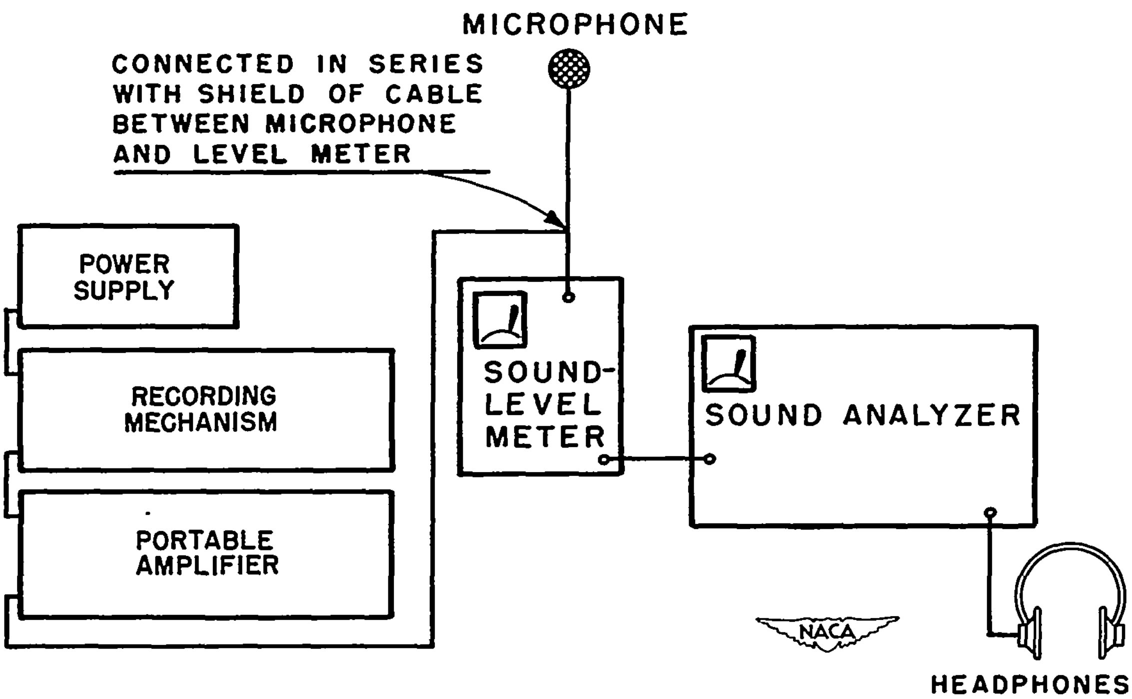


Figure 14.- Frequency response of sound-level meter and sound analyzer. Measured with constant voltage applied in series with sound-level-meter microphone.



(a) For magnetic tape recording of flight noise.



(b) For analysis of magnetic tape recordings.

Figure 15.- Equipment interconnections.

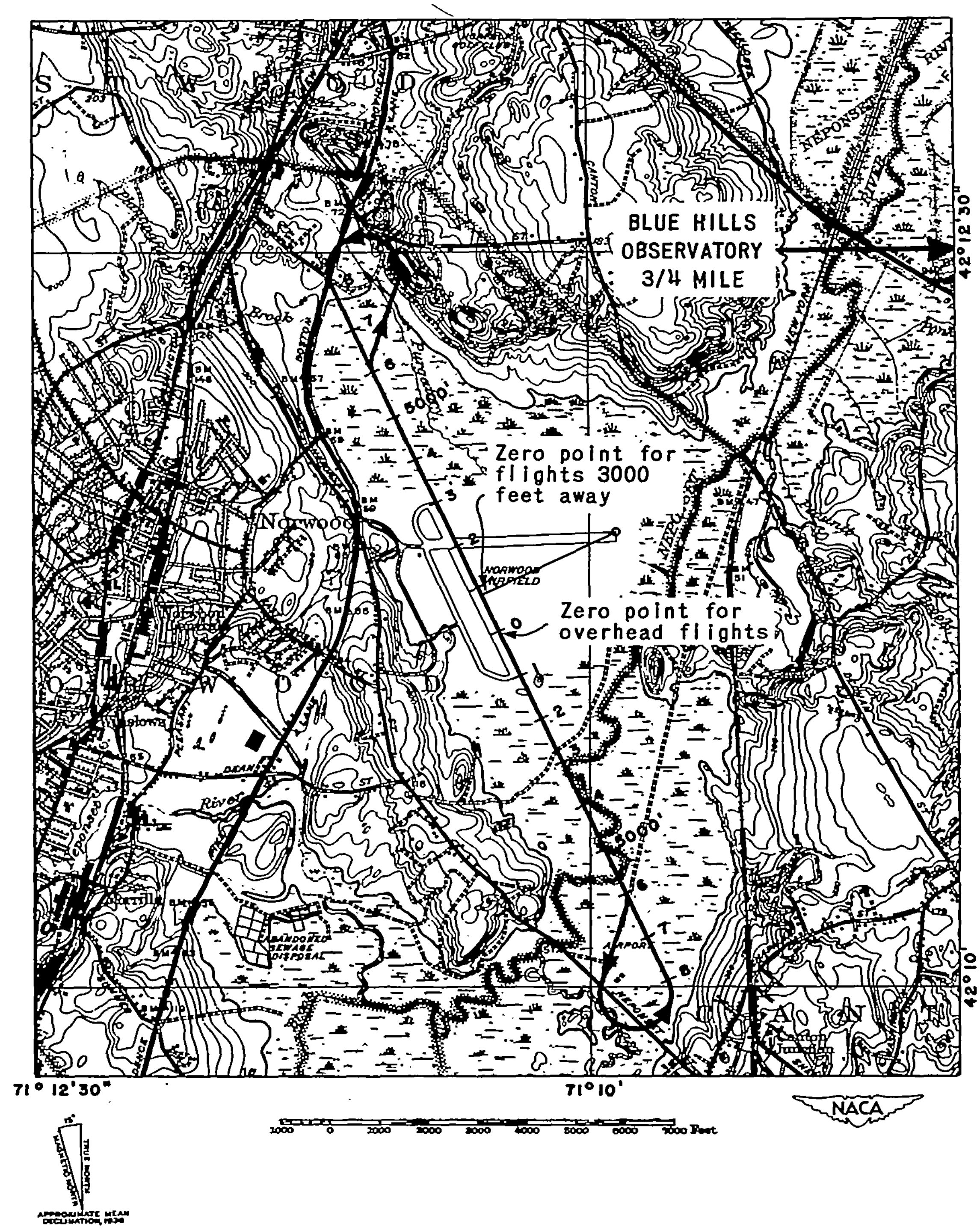
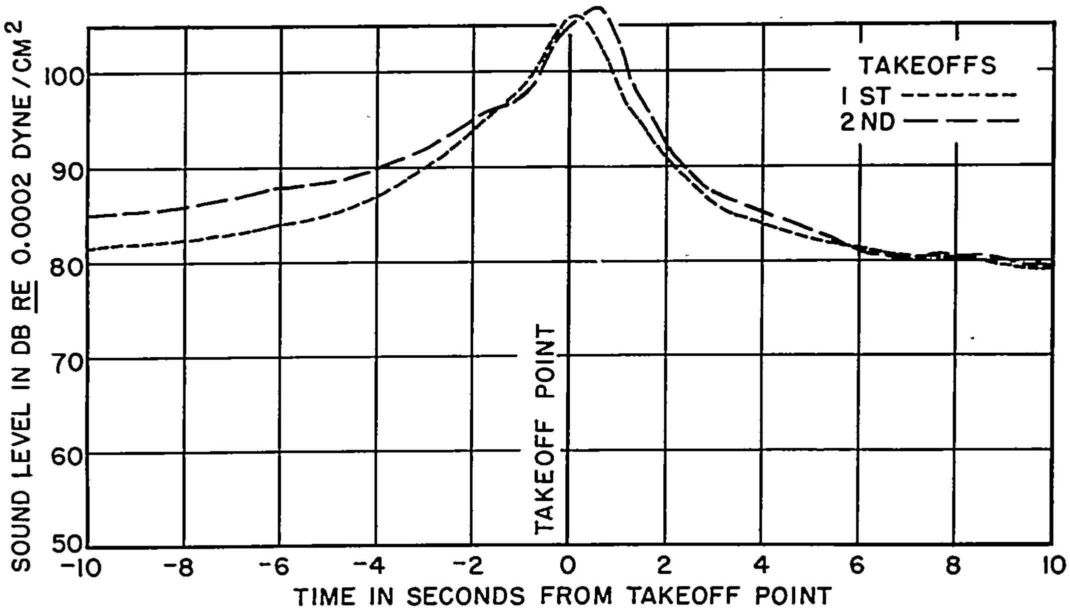
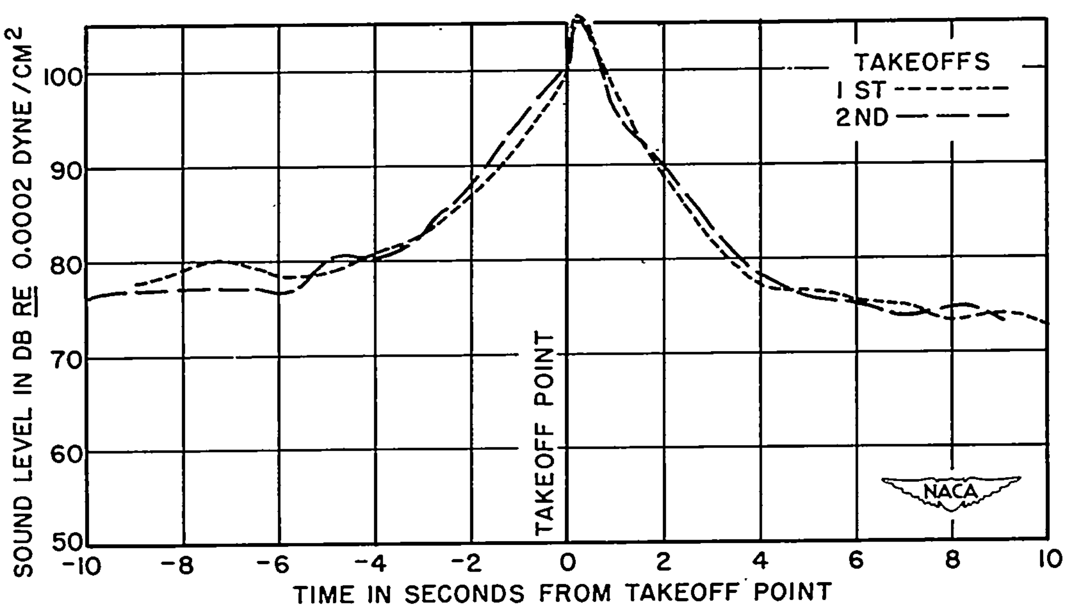


Figure 16.- Map of sound test site. Sound equipment at zero point of flight course for overhead flights; sound equipment at position indicated by small circle at end of east-west runway for flights passing 3000 feet away.

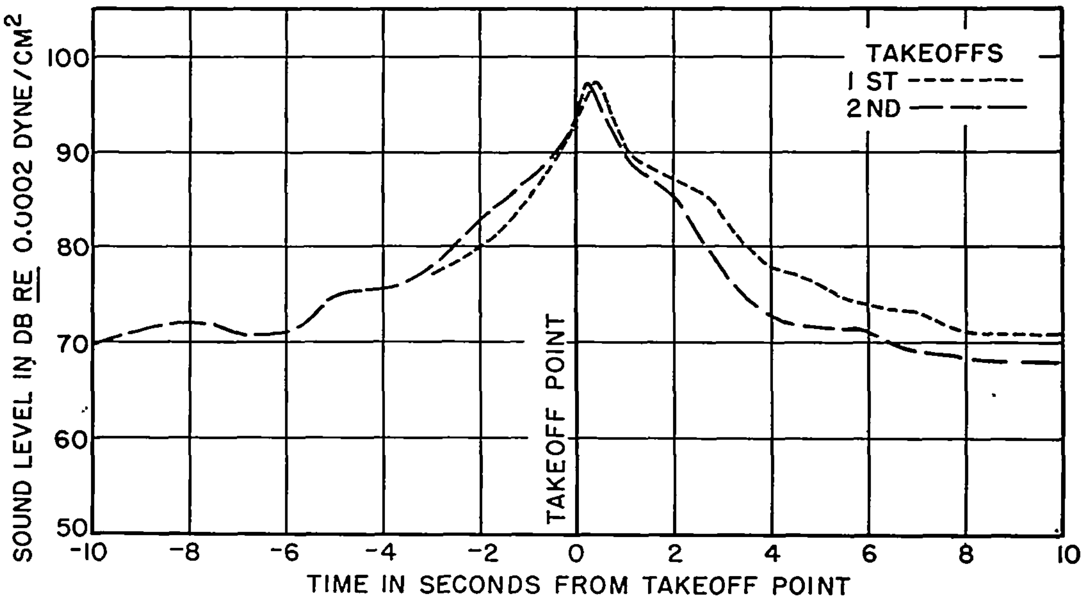


(a) Configuration 6 - standard pusher, Aeromatic propeller. 2500 to 2600 rpm.

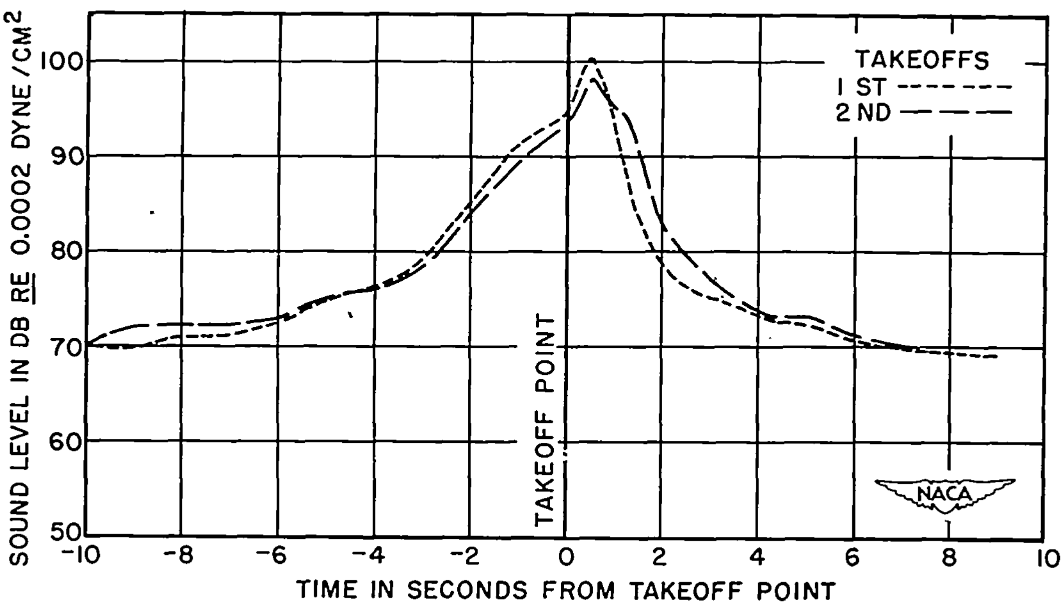


(b) Configuration 9A - modified pusher, three-bladed propeller. 2500 rpm.

Figure 17.- Comparison of take-off measurements for configurations of series A. Flat weighting; airplane leaving ground as it passes 50 feet from microphone. Refer to table II for engine powers, tip speeds, and propeller diameters. RE indicates "referred to a level of."

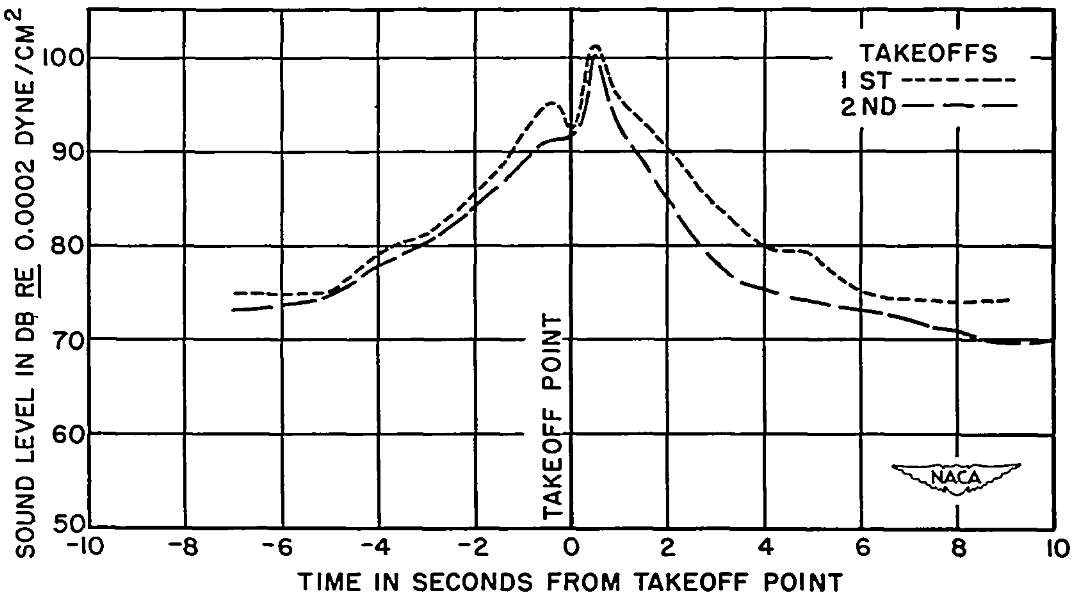


(c) Configuration 9B - modified pusher, four-bladed propeller. 2500 rpm.



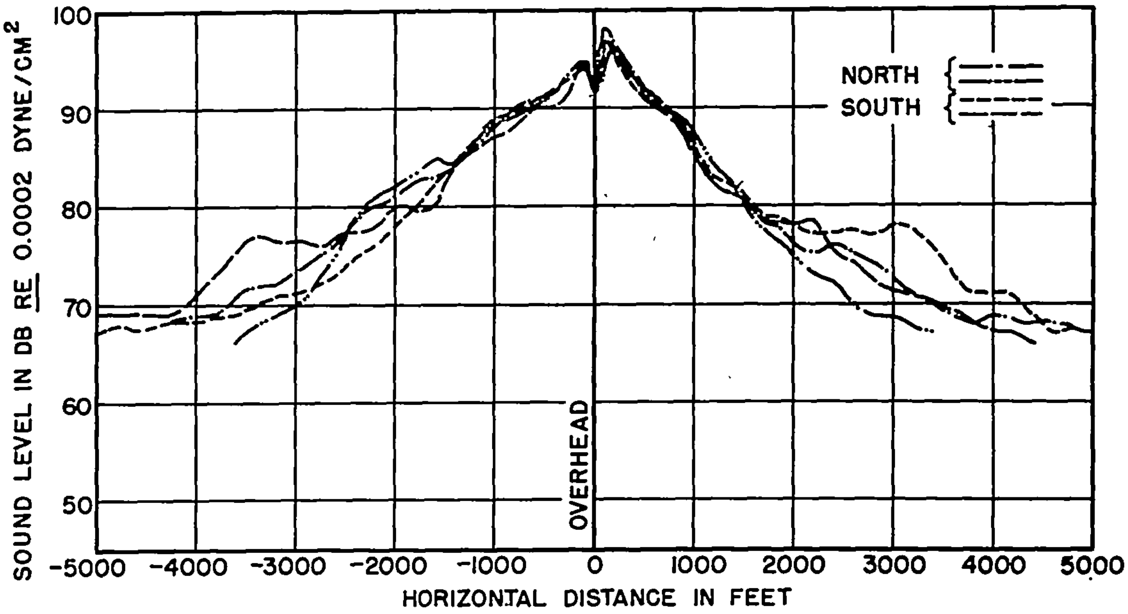
(d) Configuration 9C - modified pusher, six-bladed propeller. 2500 rpm.

Figure 17.- Continued.

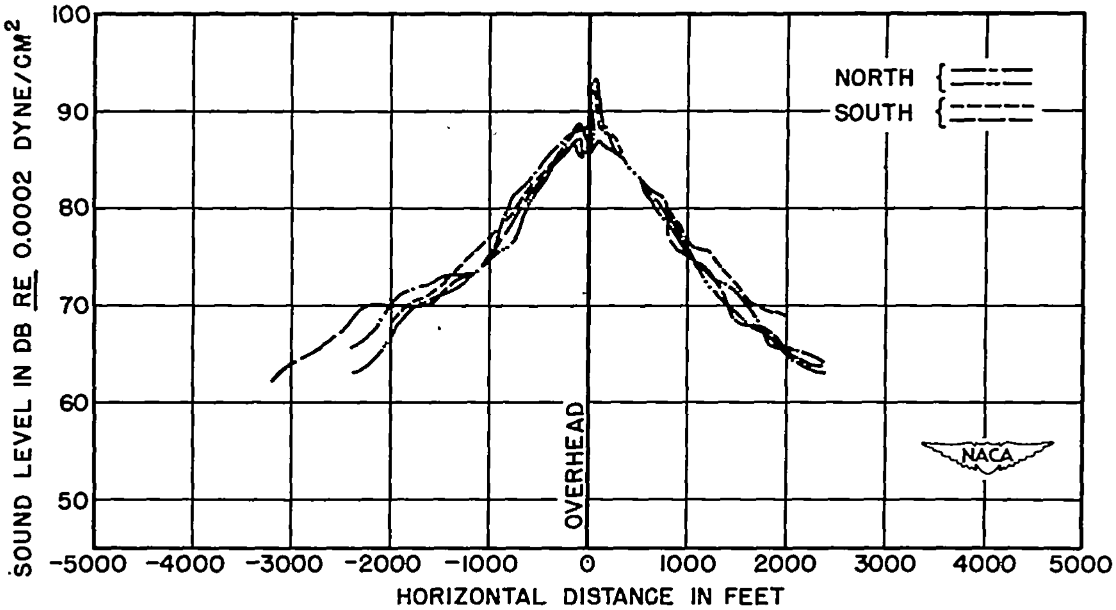


(e) Configuration 9D - modified pusher, eight-bladed propeller. 2500 rpm.

Figure 17.- Concluded.

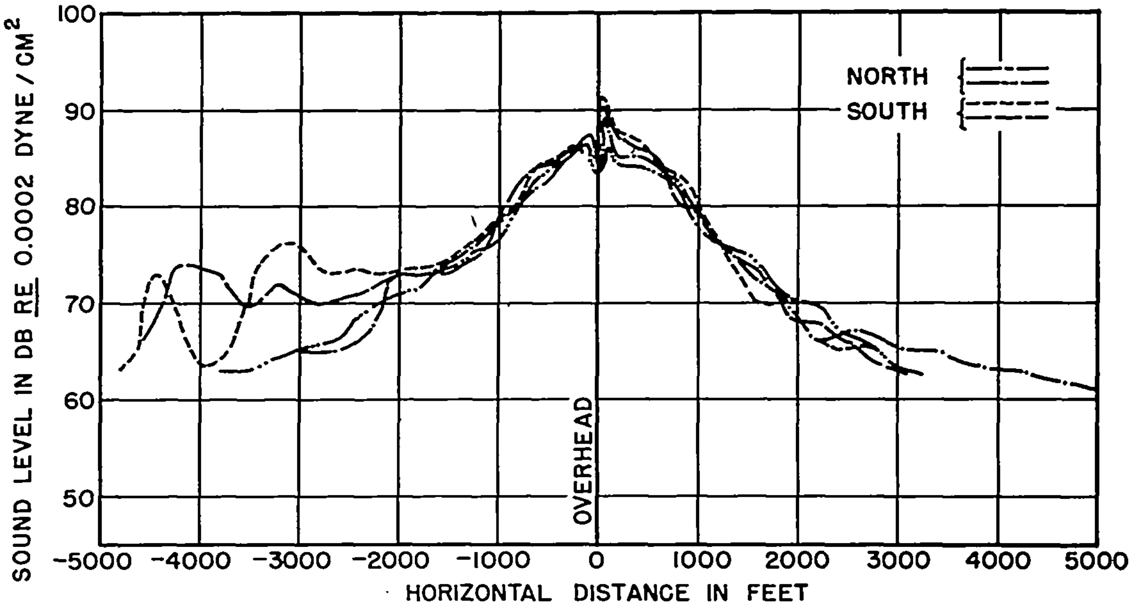


(a) Configuration 6 - standard pusher, Aeromatic propeller. 2600 rpm; wind - southeast, 1 mph.

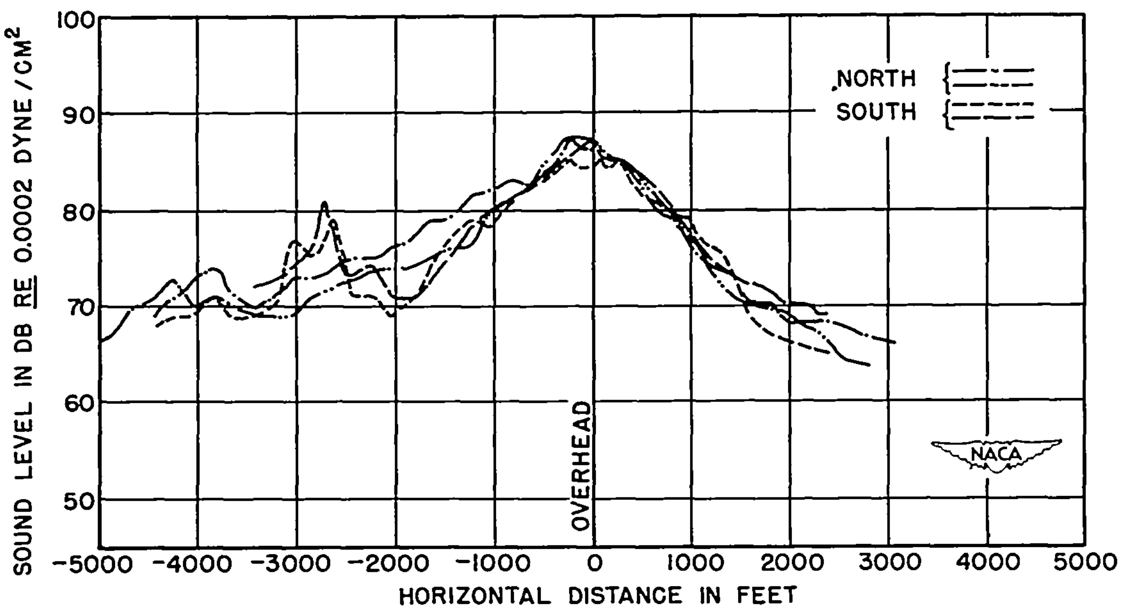


(b) Configuration 9A - modified pusher, three-bladed propeller. 2500 rpm; wind - east, 1 mph.

Figure 18.- Comparison of flight measurements for configurations of series A. Flights at 100-foot altitude; maximum power; flat weighting; airplane passing overhead. Refer to table II for engine powers, tip speeds, and propeller diameters. RE indicates "referred to a level of."

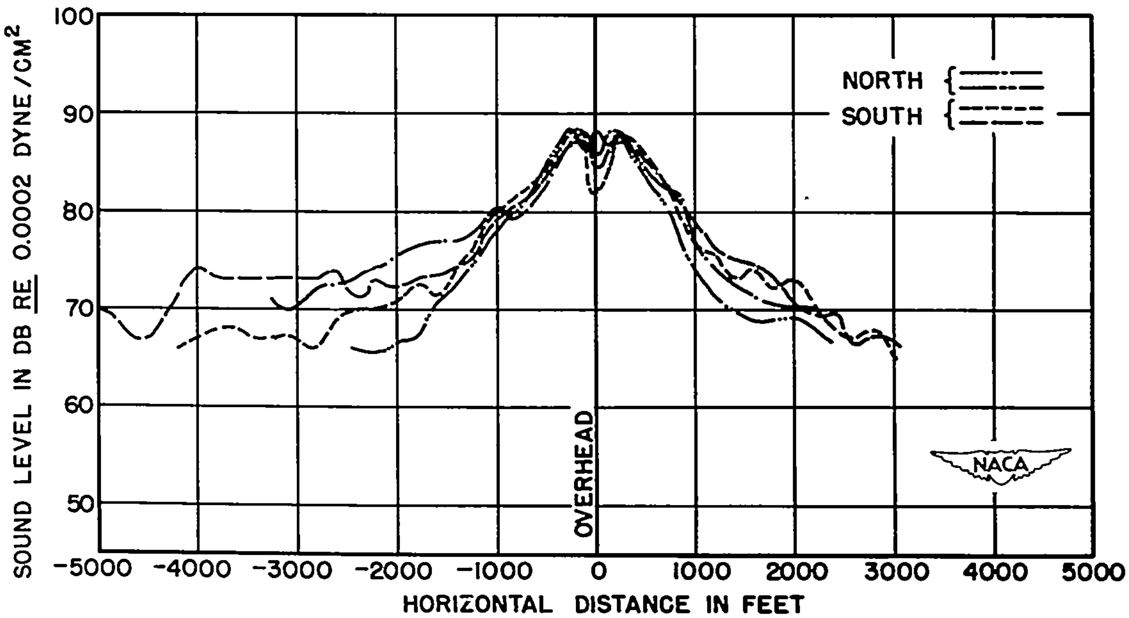


(c) Configuration 9B - modified pusher, four-bladed propeller. 2500 rpm; wind - west, 1 mph.



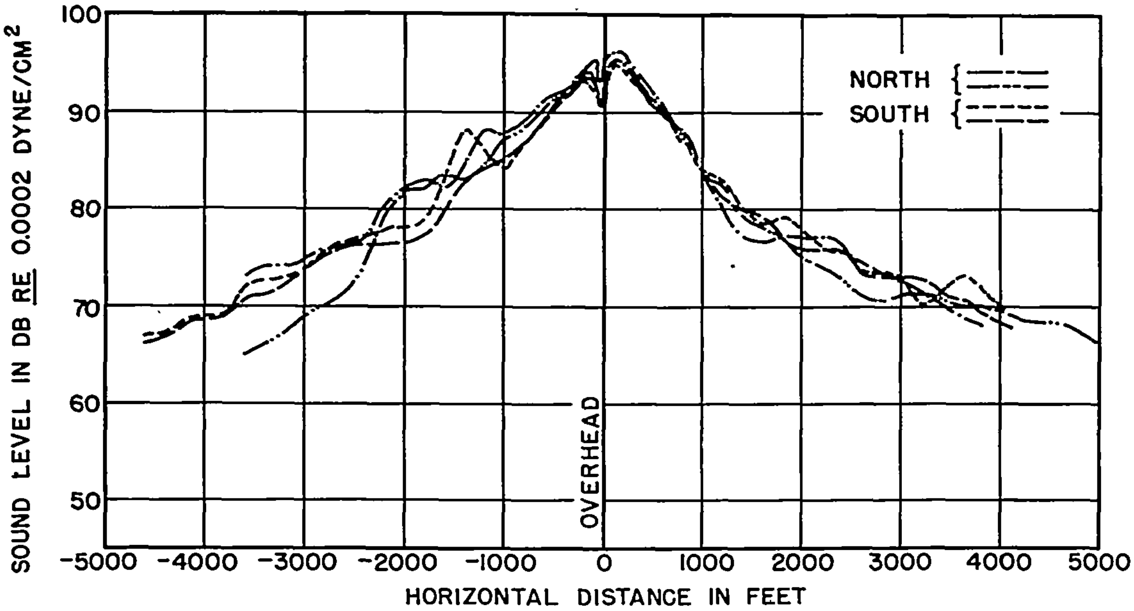
(d) Configuration 9C - modified pusher, six-bladed propeller. 2500 rpm; wind - 0 mph.

Figure 18.- Continued.

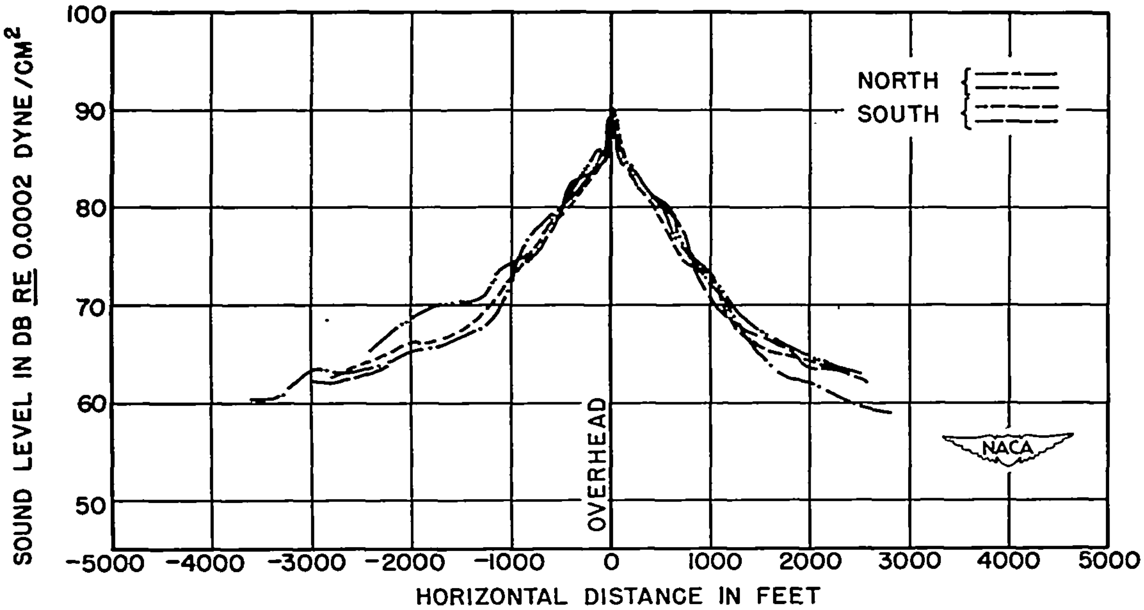


(e) Configuration 9D - modified pusher, eight-bladed propeller. 2500 rpm; wind - west, 2 mph.

Figure 18.- Concluded.

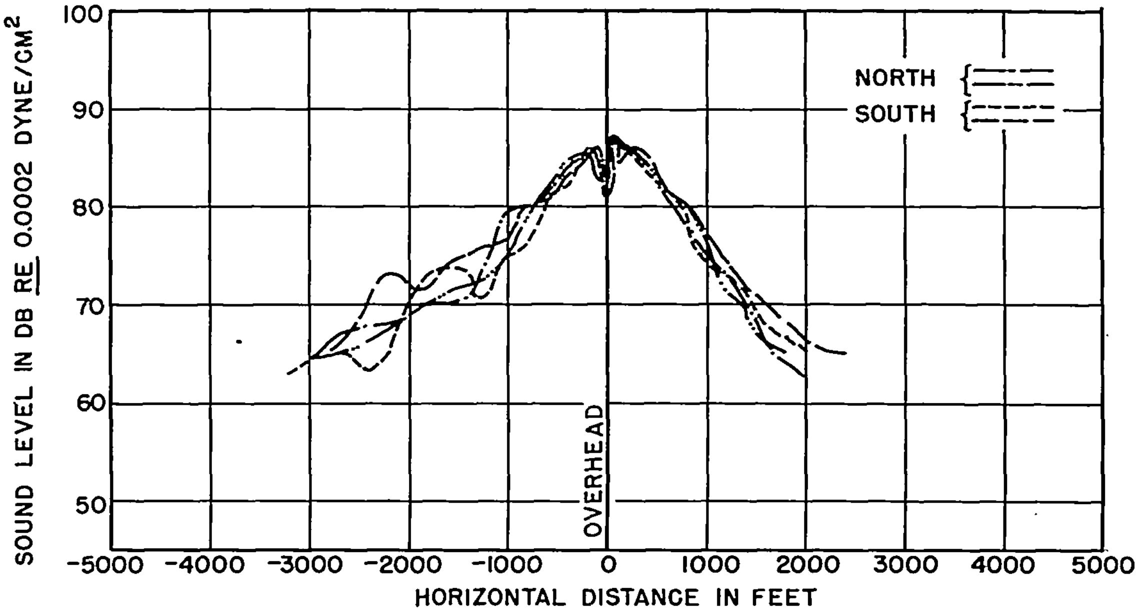


(a) Configuration 6 - standard pusher, Aeromatic propeller. 2450 rpm; wind - south, 1 mph.

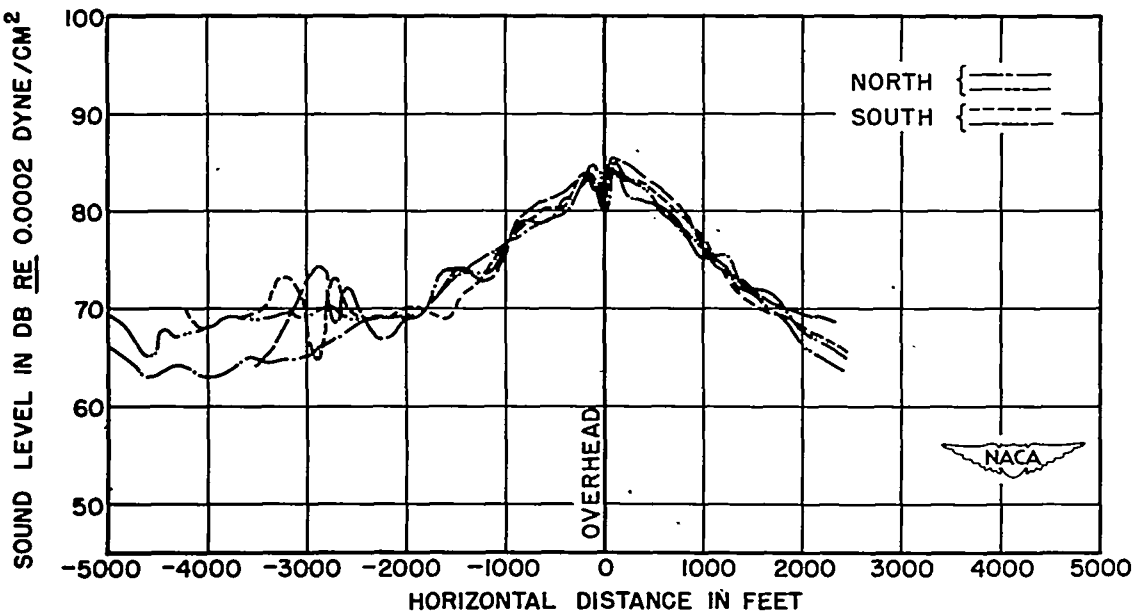


(b) Configuration 9A - modified pusher, three-bladed propeller. 2250 rpm; wind - east, 1 mph.

Figure 19.- Comparison of flight measurements for configurations of series A. Flights at 100-foot altitude; cruising power; flat weighting; airplane passing overhead. Refer to table II for engine powers, tip speeds, and propeller diameters. RE indicates "referred to a level of."

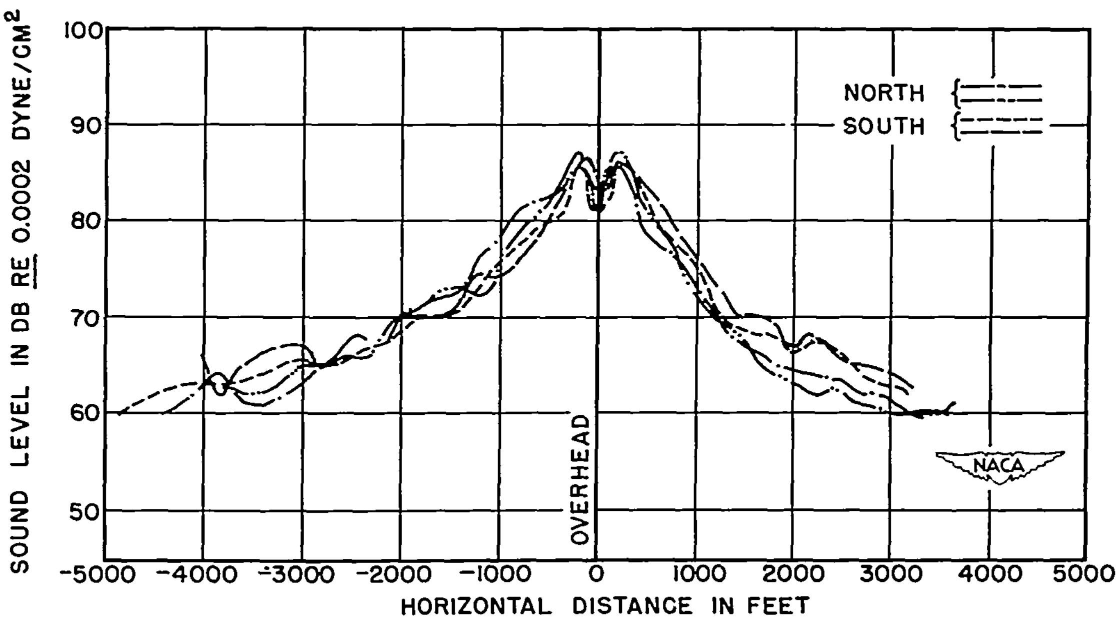


(c) Configuration 9B - modified pusher, four-bladed propeller. 2250 rpm; wind - 0 mph.



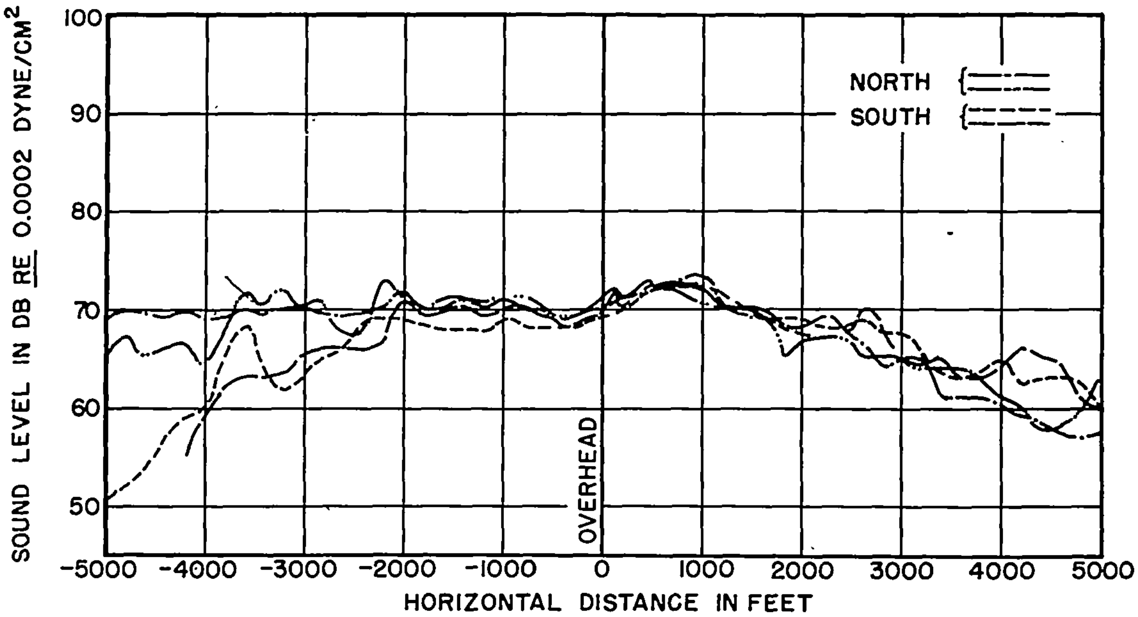
(d) Configuration 9C - modified pusher, six-bladed propeller. 2250 rpm; wind - 0 mph.

Figure 19.- Continued.

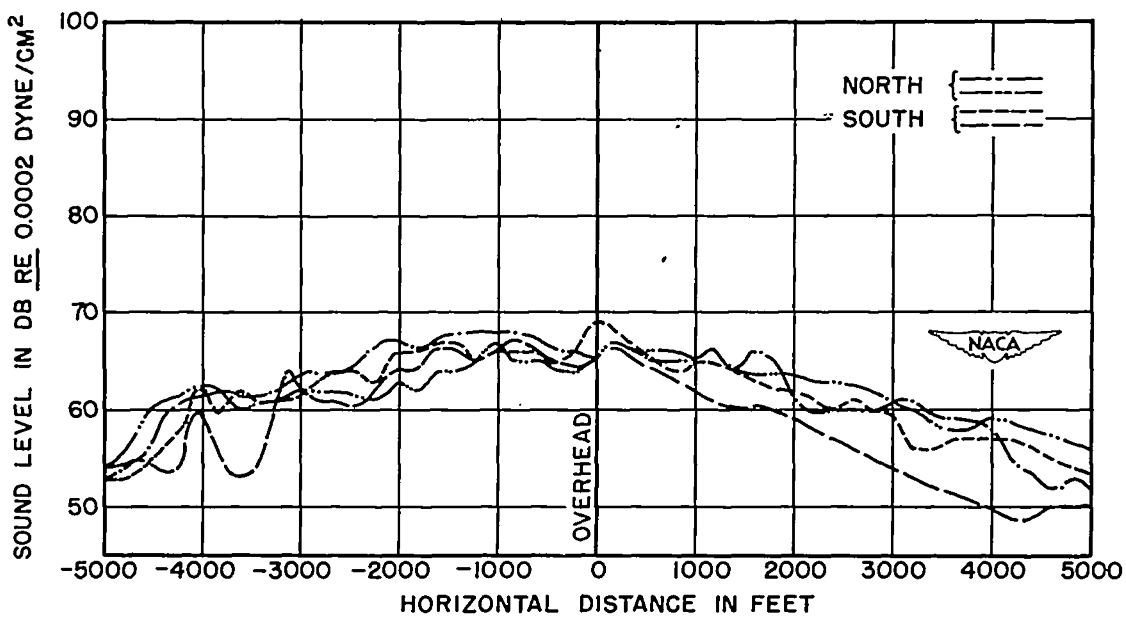


(e) Configuration 9D - modified pusher, eight-bladed propeller. 2250 rpm; wind - west, 2 mph.

Figure 19.- Concluded.

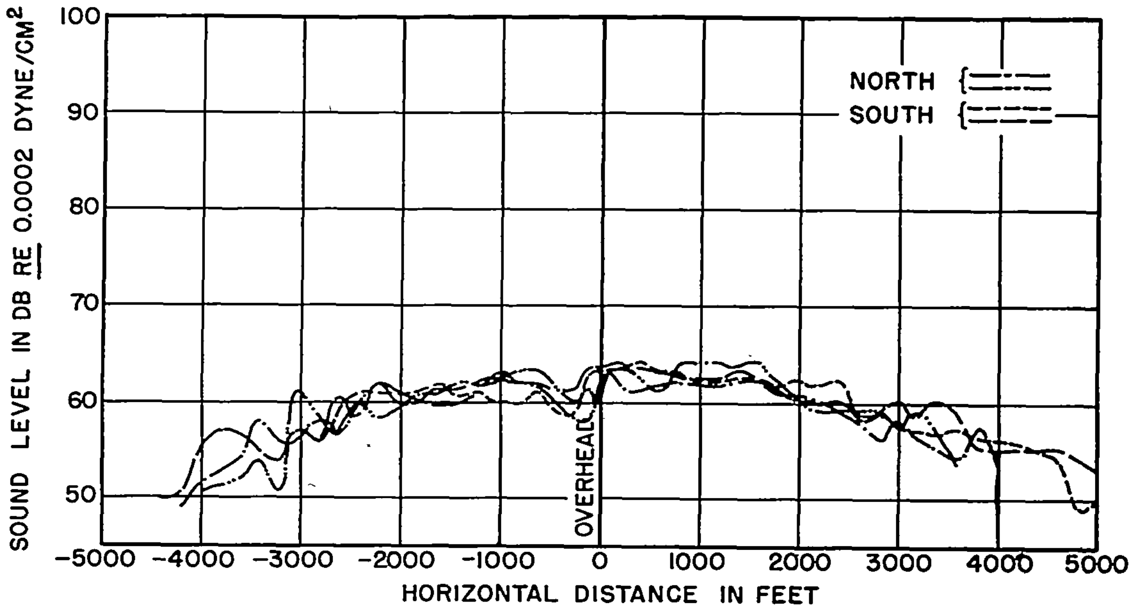


(a) Configuration 6 - standard pusher, Aeromatic propeller. 2600 rpm; wind - northeast, 2 mph.

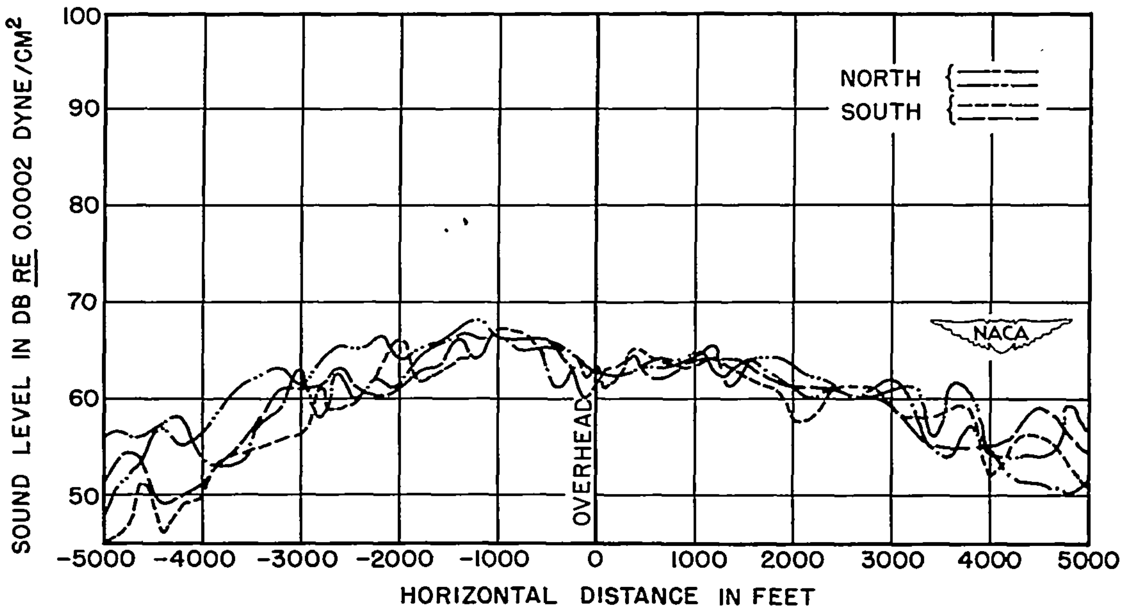


(b) Configuration 9A - modified pusher, three-bladed propeller. 2500 rpm; wind - east, 1 mph.

Figure 20.- Comparison of flight measurements for configurations of series A. Flights at 500-foot altitude; maximum power; 40-decibel weighting; airplane passing overhead. Refer to table II for engine powers, tip speeds, and propeller diameters. RE indicates "referred to a level of."

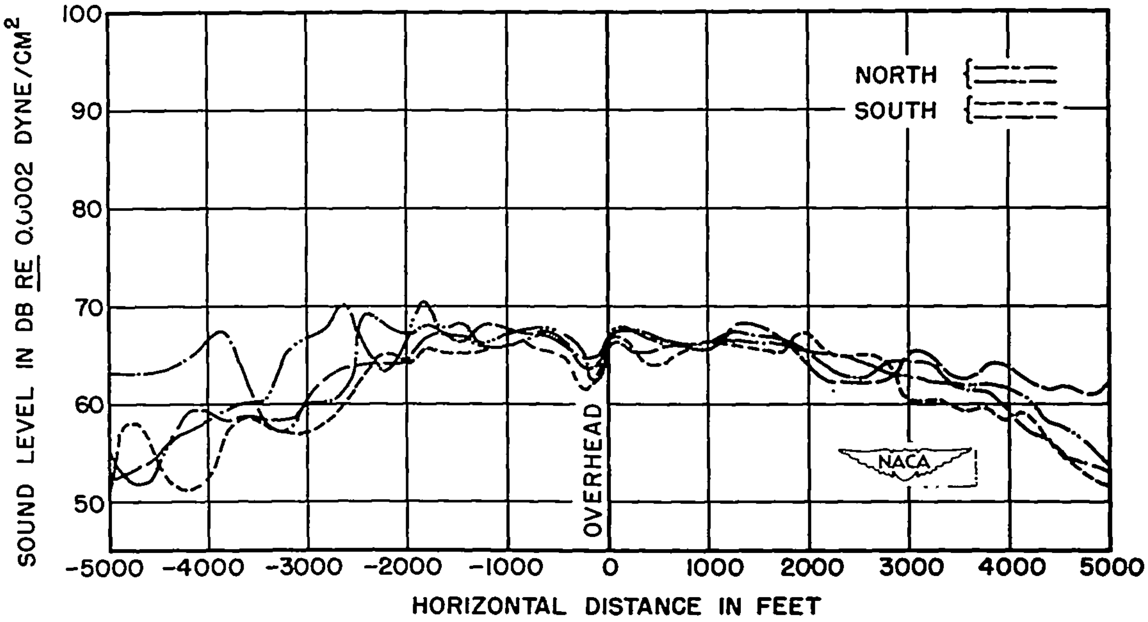


(c) Configuration 9B - modified pusher, four-bladed propeller. 2500 rpm; wind - east, 3 mph.



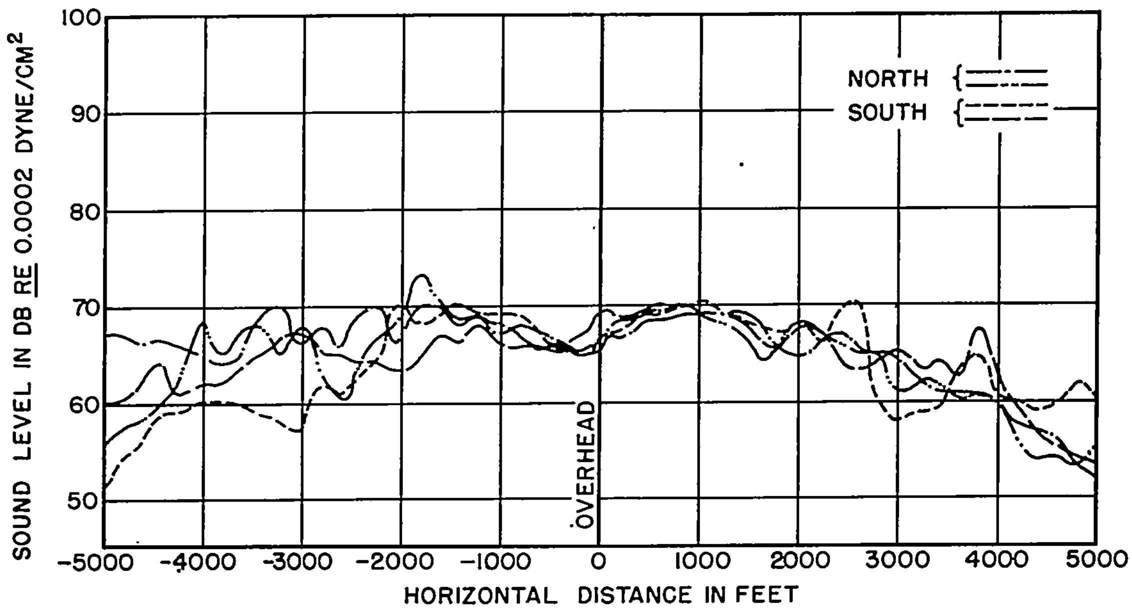
(d) Configuration 9C - modified pusher, six-bladed propeller. 2500 rpm; wind - north, 2 mph.

Figure 20.- Continued.

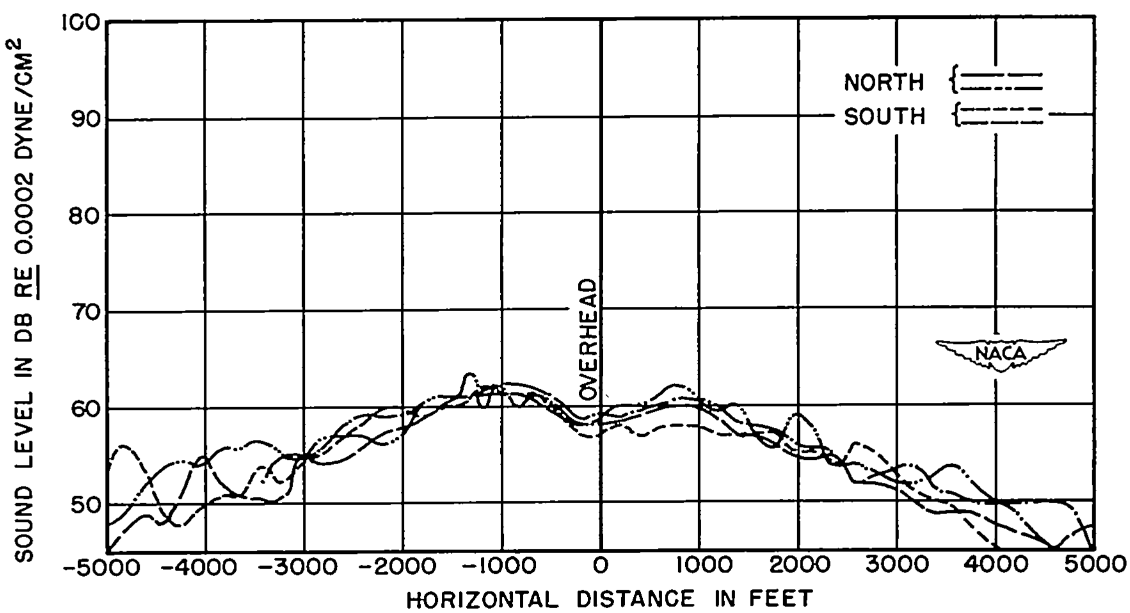


(e) Configuration 9D - modified pusher, eight-bladed propeller. 2500 rpm; wind - east, 1 mph.

Figure 20.- Concluded.

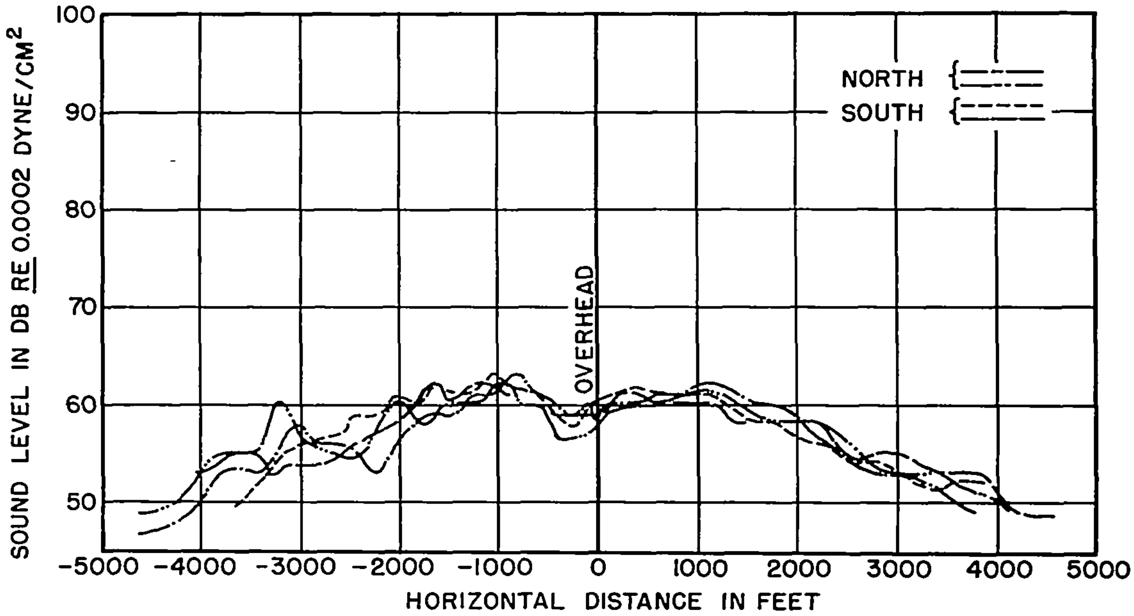


(a) Configuration 6 - standard pusher, Aeromatic propeller. 2450 rpm; wind - northeast, 2 mph.

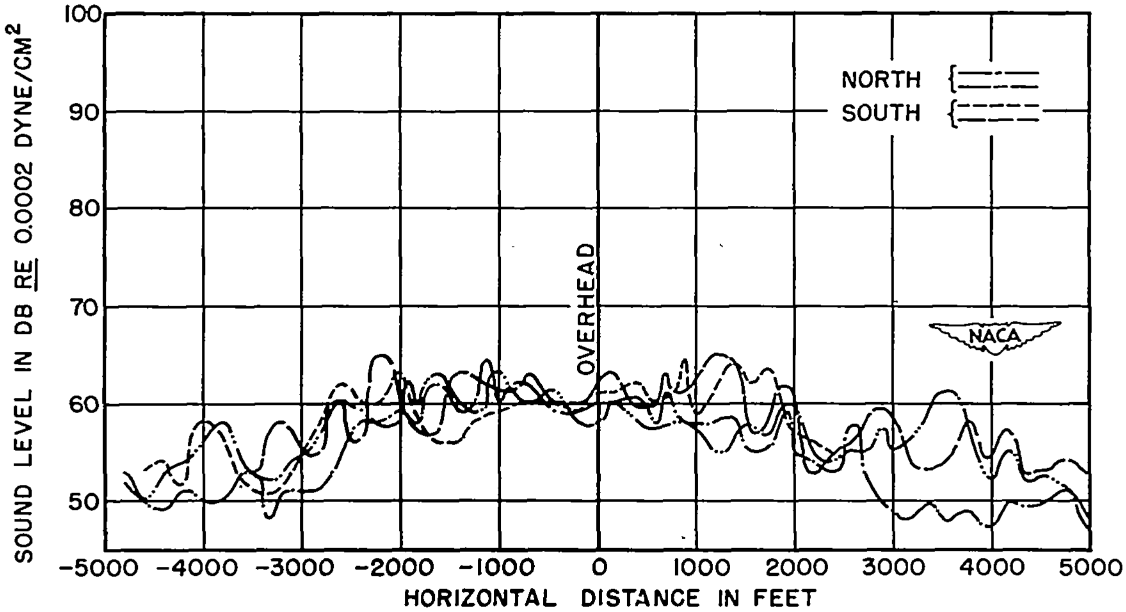


(b) Configuration 9A - modified pusher, three-bladed propeller. 2250 rpm; wind - east, 1 mph.

Figure 21.- Comparison of flight measurements for configurations of series A. Flights at 500-foot altitude; cruising power; 40-decibel weighting; airplane passing overhead. Refer to table II for engine powers, tip speeds, and propeller diameters. RE indicates "referred to a level of."

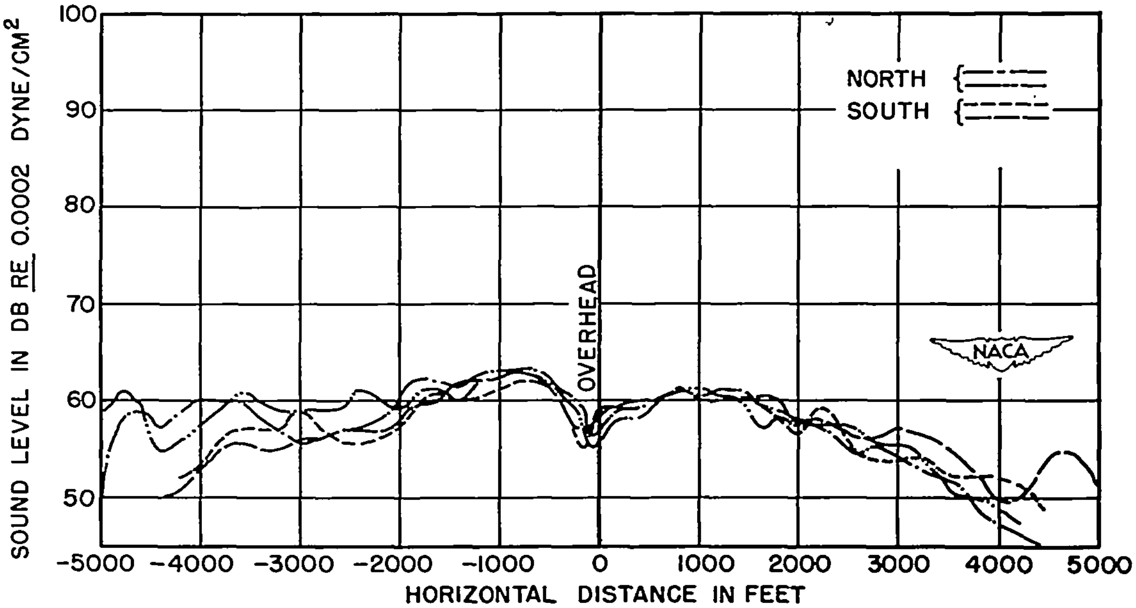


(c) Configuration 9B - modified pusher, four-bladed propeller. 2250 rpm; wind - east, 3 mph.



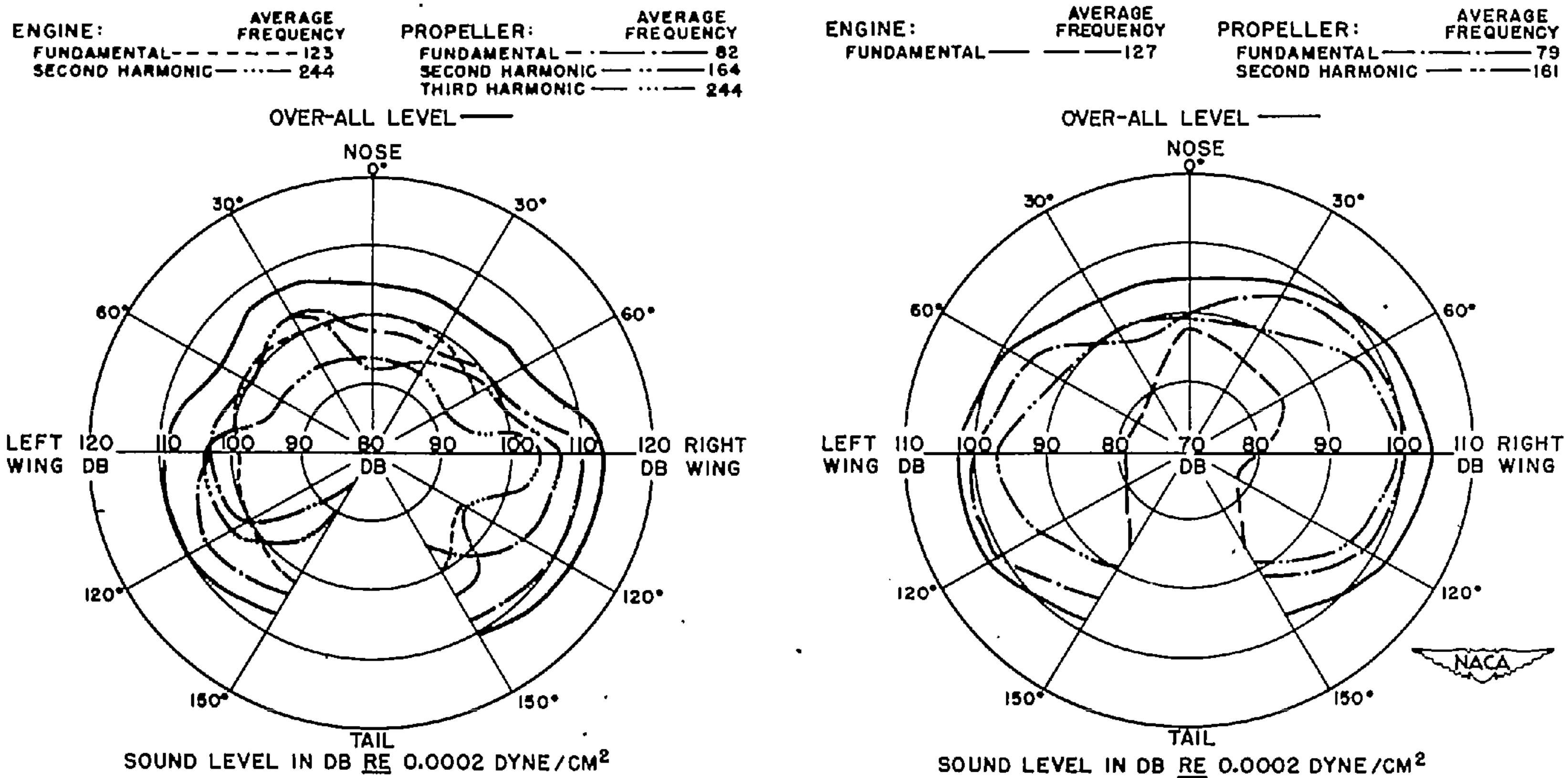
(d) Configuration 9C - modified pusher, six-bladed propeller. 2250 rpm; wind - west, 6 mph.

Figure 21.- Continued.



(e) Configuration 9D - modified pusher, eight-bladed propeller. 2250 rpm; wind - east, 1 mph.

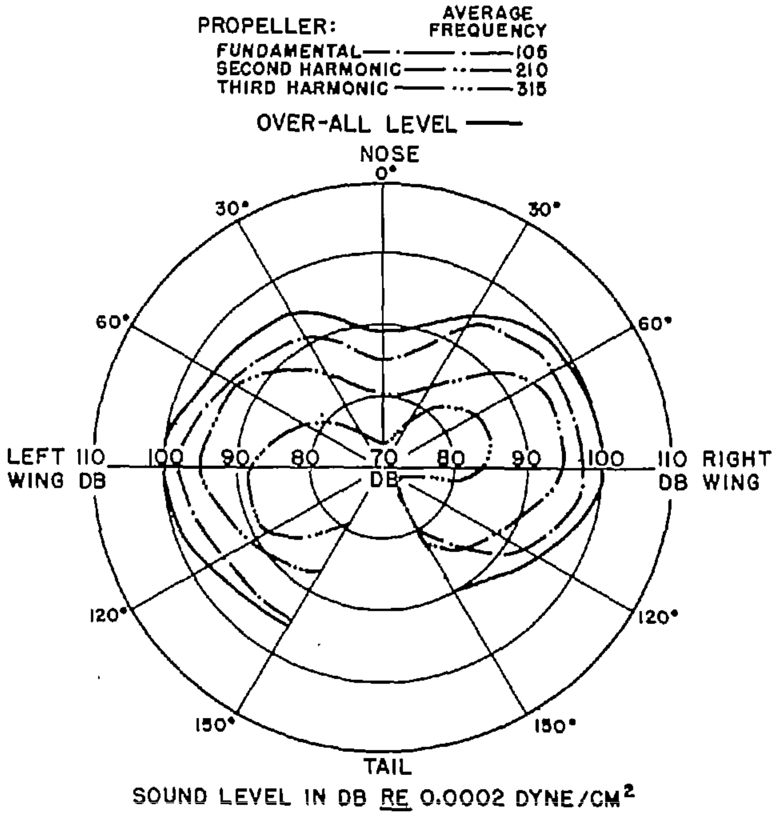
Figure 21.- Concluded.



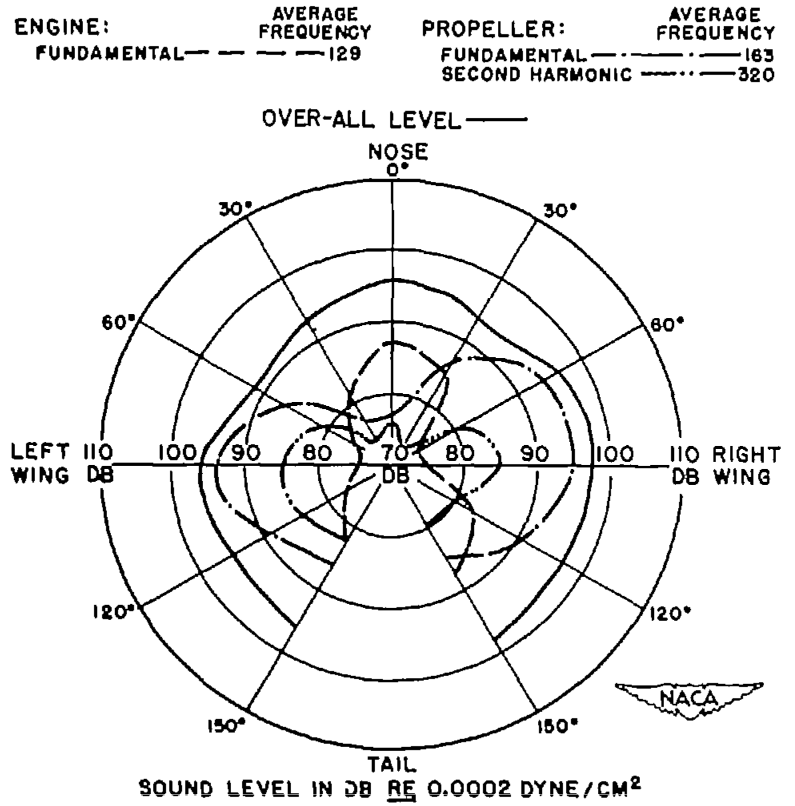
(a) Configuration 6 - standard pusher, Aeromatic propeller. 2500 rpm; engine second harmonic and propeller third harmonic occur at same frequency; engine fundamental not measurable at 90° right position.

(b) Configuration 9A - modified pusher, three-bladed propeller. 2500 rpm.

Figure 22.- Comparison of ground analyses for configurations of series A. Frequency analysis on ground 50 feet from hub; flat weighting. Refer to table II for engine powers, tip speeds, and propeller diameters. RE indicates "referred to a level of."

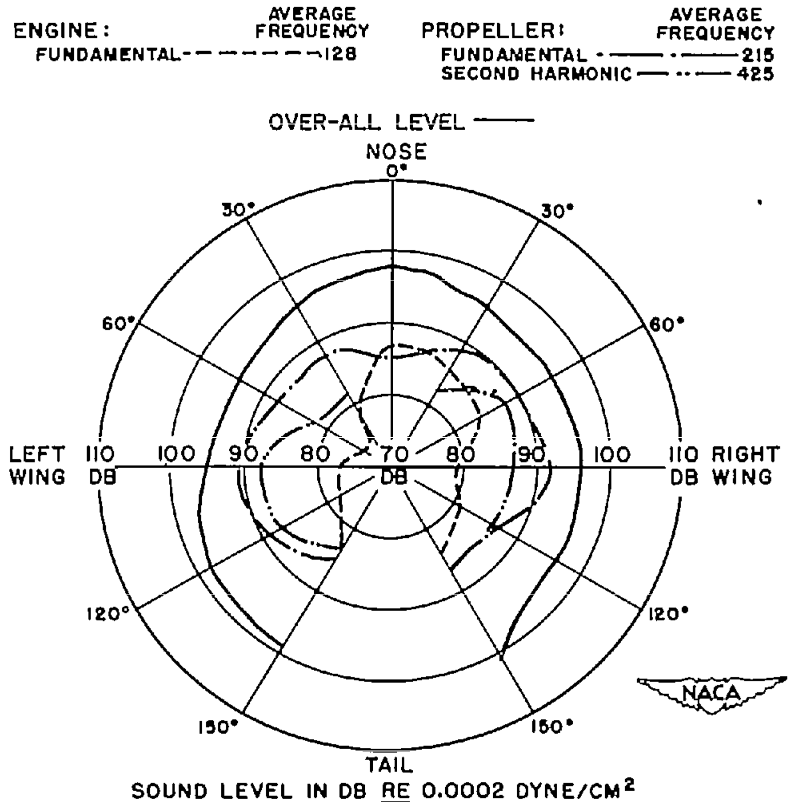


(c) Configuration 9B - modified pusher, four-bladed propeller. 2475 rpm; engine noise masked by propeller.



(d) Configuration 9C - modified pusher, six-bladed propeller. 2500 rpm.

Figure 22.- Continued.



(e) Configuration 9D - modified pusher, eight-bladed propeller. 2500 rpm.

Figure 22.- Concluded.

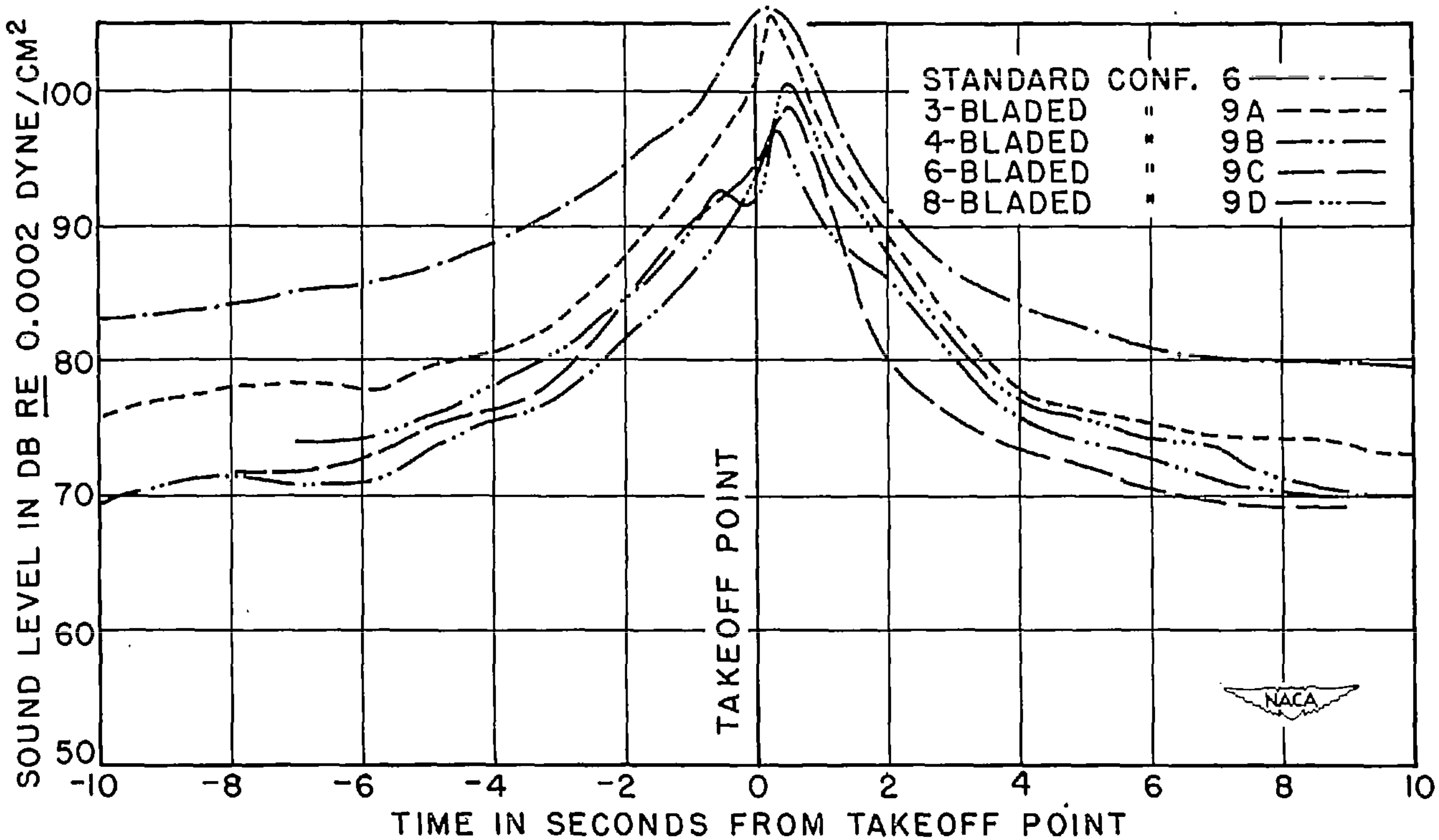


Figure 23.- Average curves of take-offs for configurations of series A. Flat weighting; airplane leaving ground 50 feet from microphone. Refer to table II for engine powers, tip speeds, and propeller diameters. RE indicates "referred to a level of."

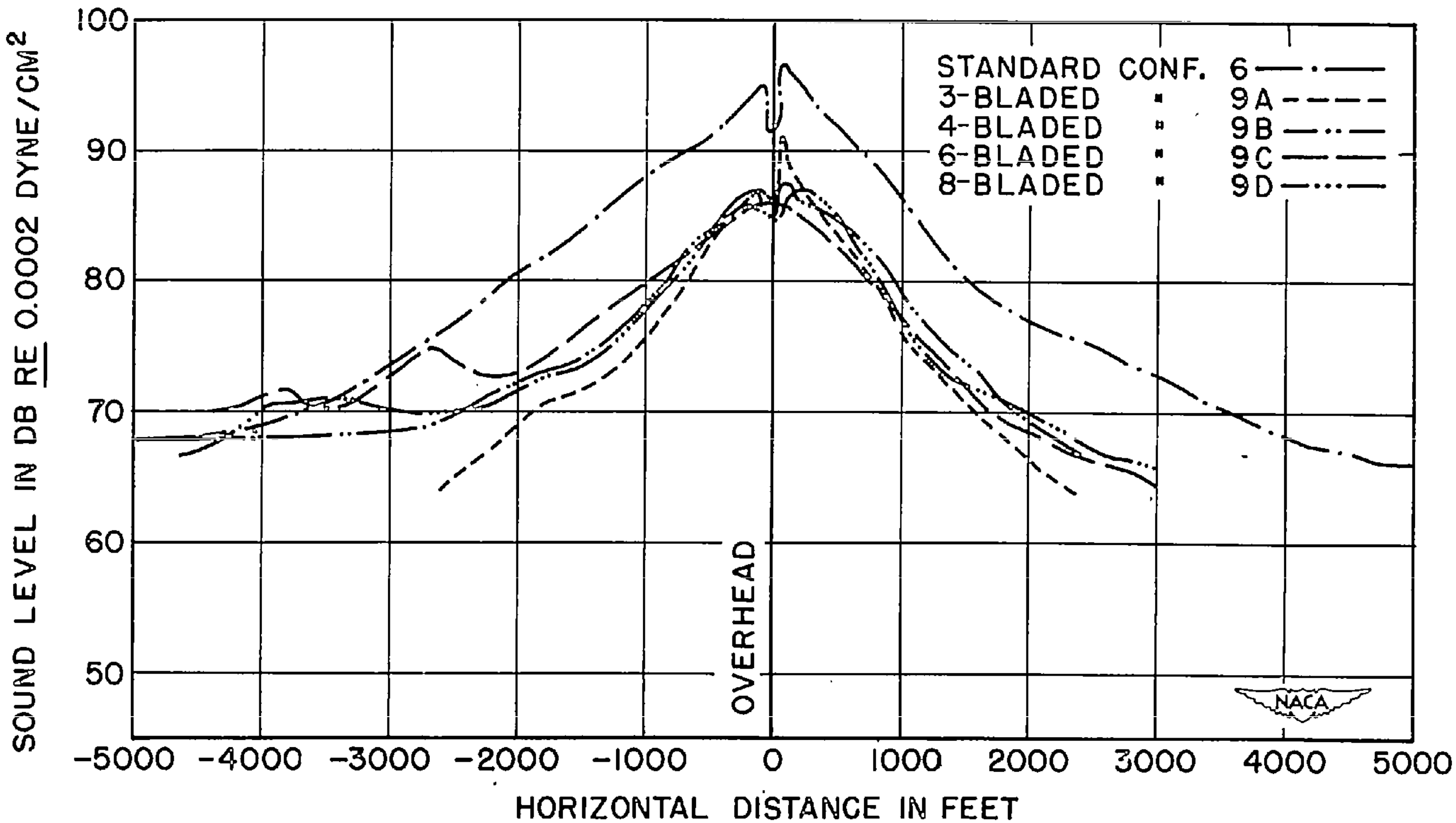


Figure 24.- Average curves of flights at 100-foot altitude for configurations of series A. Maximum power; flat weighting. Refer to table II for engine powers, tip speeds, and propeller diameters. RE indicates "referred to a level of."

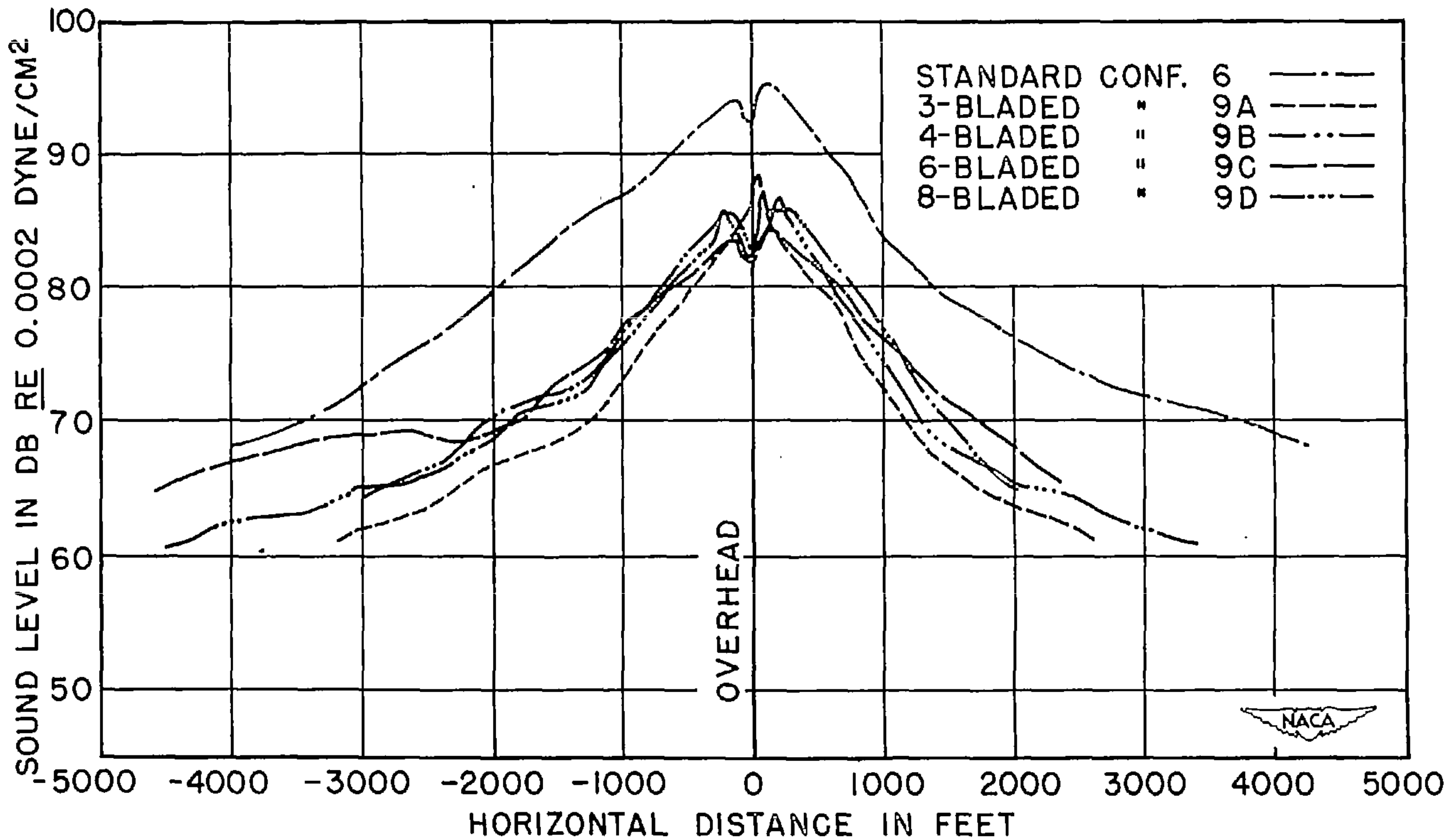


Figure 25.- Average curves of flights at 100-foot altitude for configurations of series A. Cruising power; flat weighting. Refer to table II for engine powers, tip speeds, and propeller diameters. RE indicates "referred to a level of."

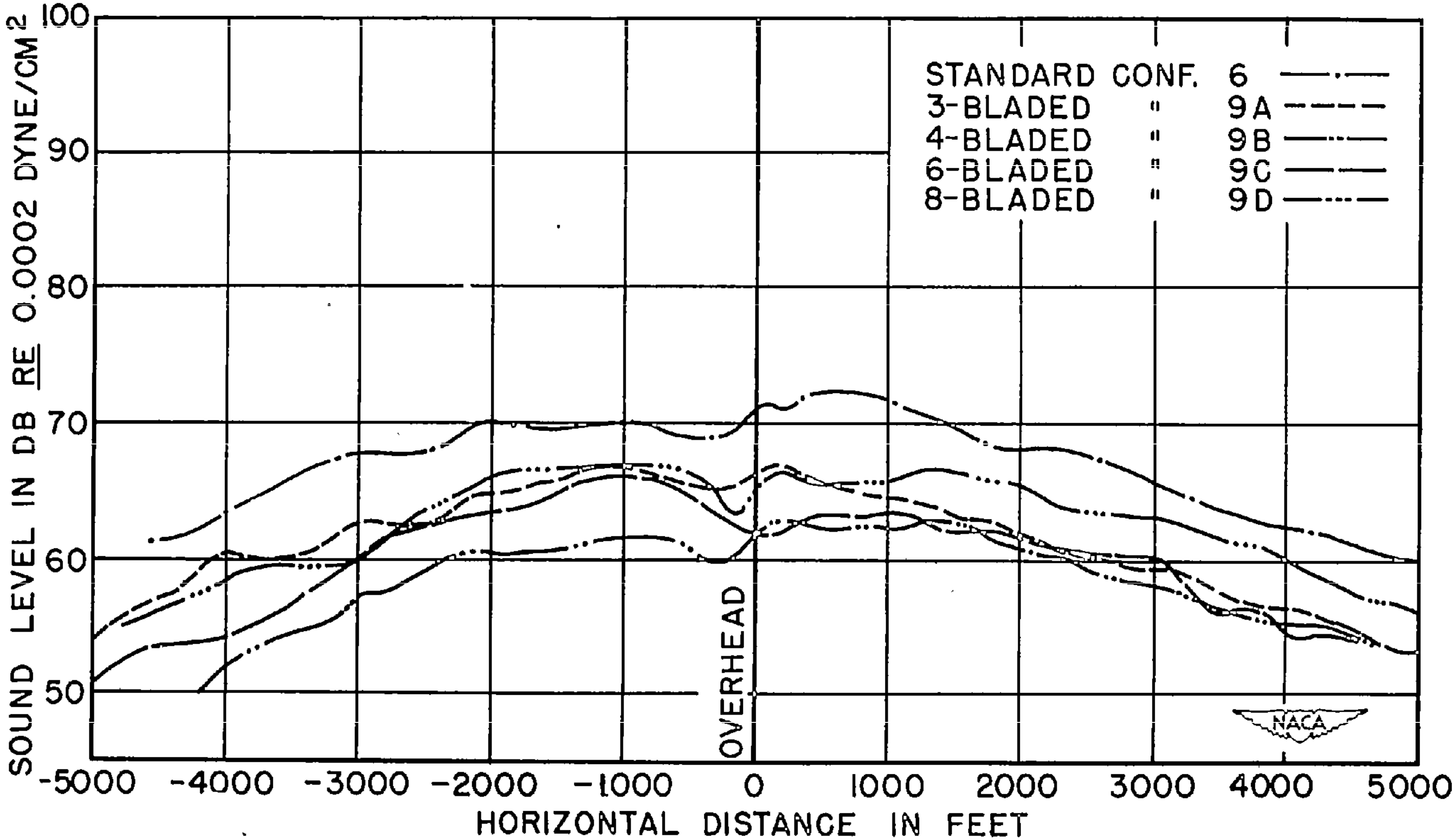


Figure 26.- Average curves of flights at 500-foot altitude for configurations of series A. Maximum power; 40-decibel weighting. Refer to table II for engine powers, tip speeds, and propeller diameters. RE indicates "referred to a level of."

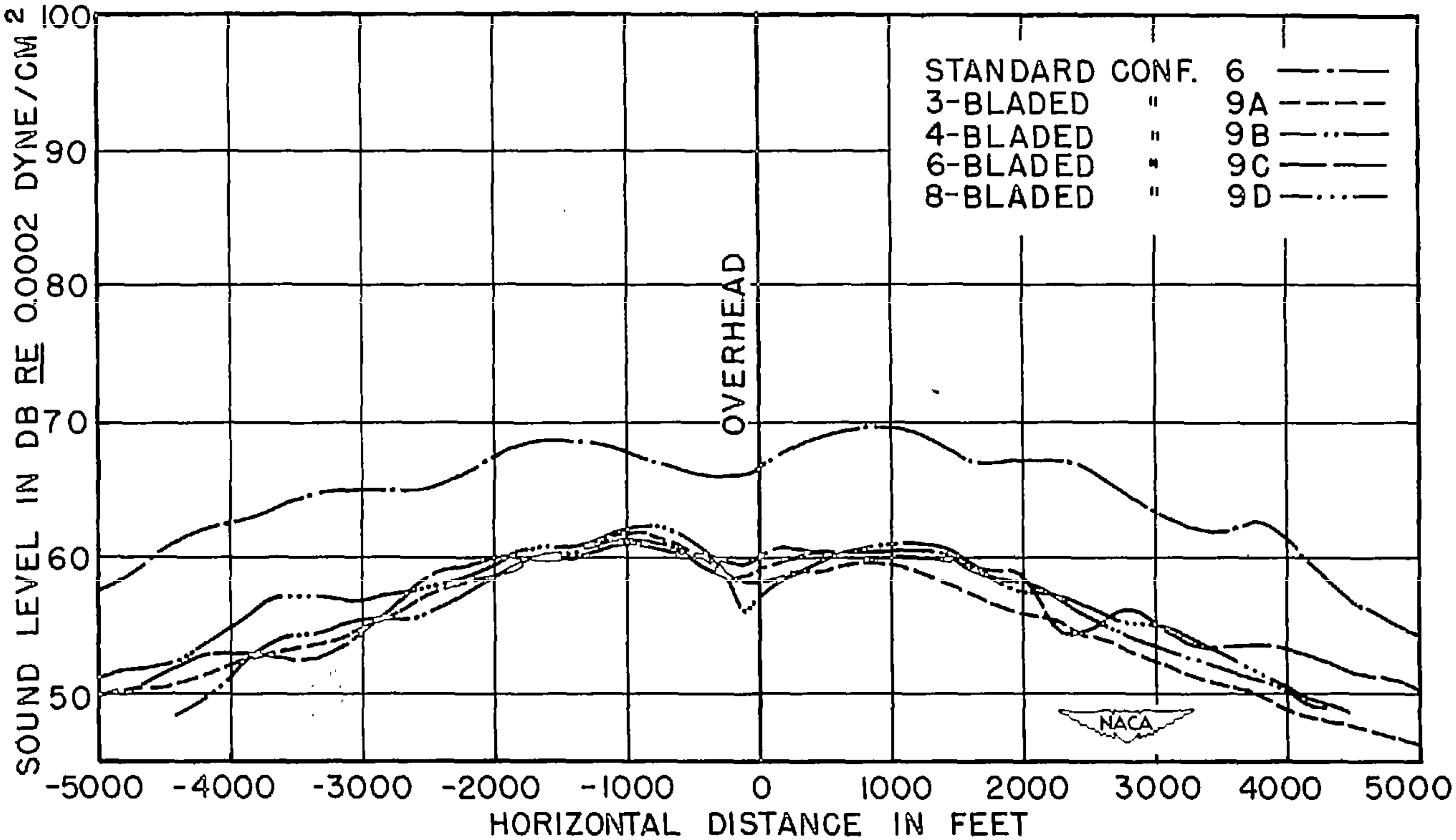


Figure 27.- Average curves of flights at 500-foot altitude for configurations of series A. Cruising power; 40-decibel weighting. Refer to table II for engine powers, tip speeds, and propeller diameters. RE indicates "referred to a level of."

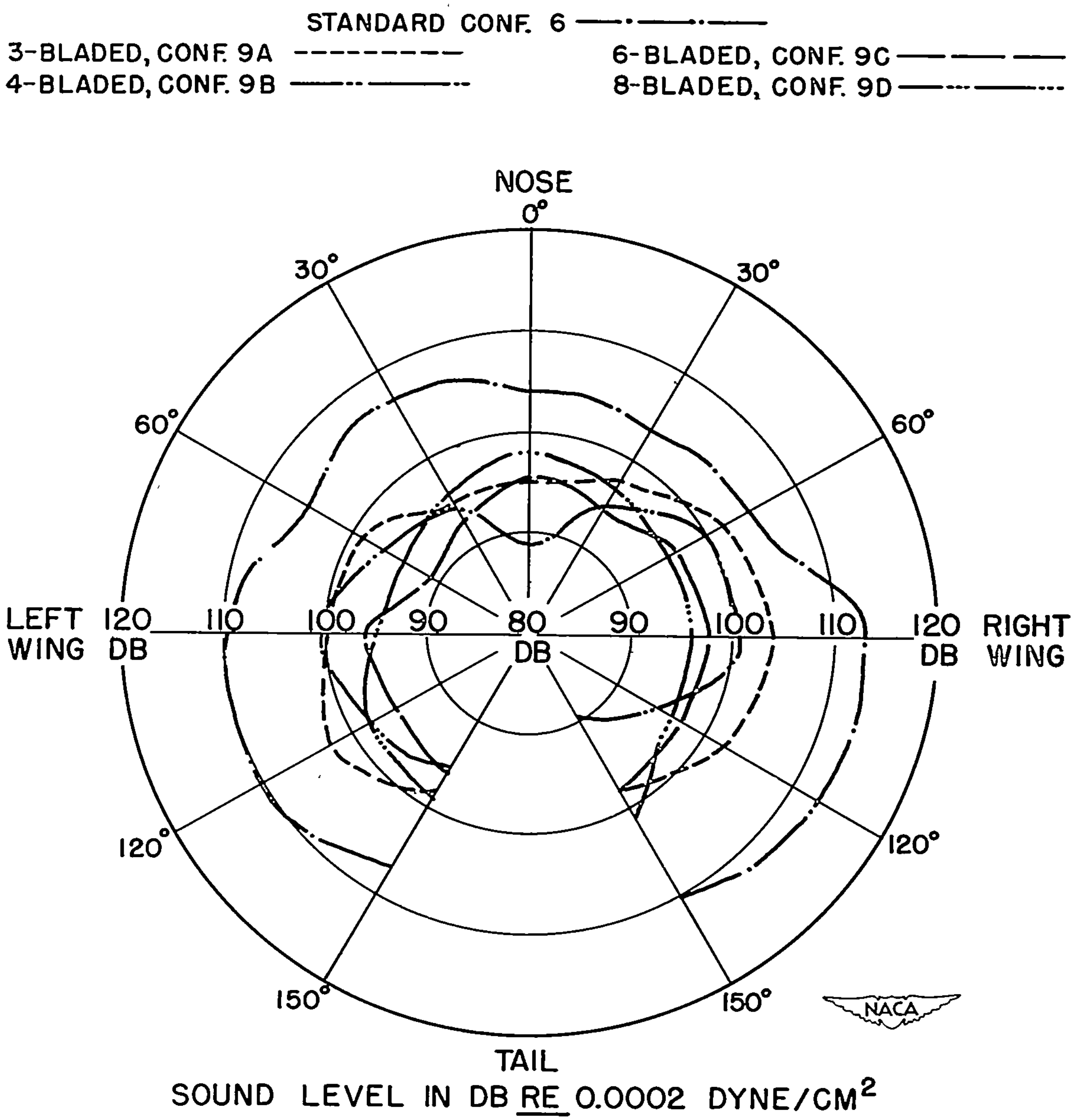


Figure 28.- Comparison of over-all sound levels for configurations of series A from frequency analysis on ground 50 feet from hub. Flat weighting. Refer to table II for engine powers, tip speeds, and propeller diameters. RE indicates "referred to a level of."

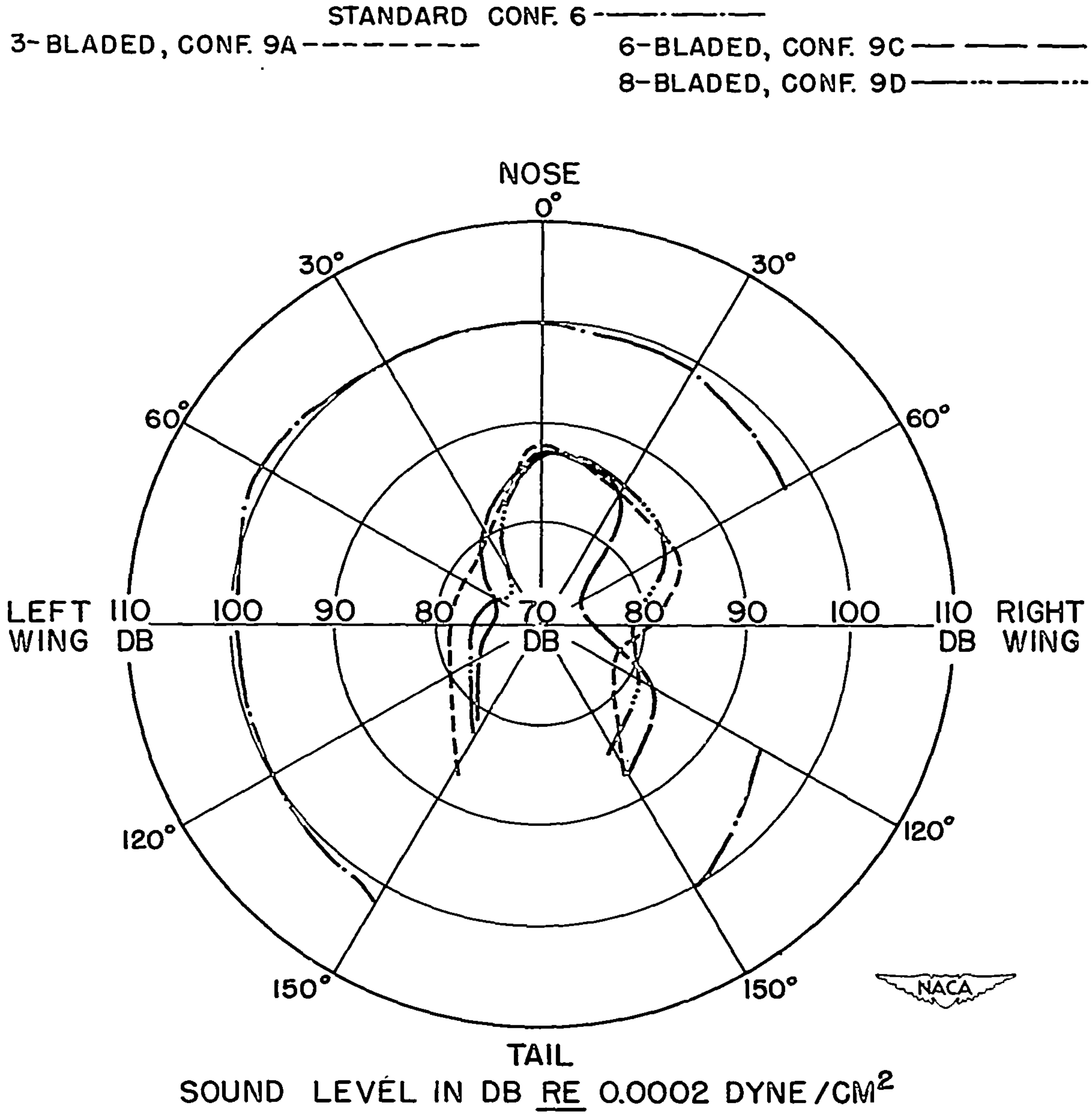


Figure 29.- Comparison of engine fundamentals for configurations of series A from frequency analysis on ground 50 feet from hub. Flat weighting. Fundamental for configuration 6 not measurable at 90° right position; fundamental for configuration 9B masked by propeller. Refer to table II for engine powers, tip speeds, and propeller diameters. RE indicates "referred to a level of."

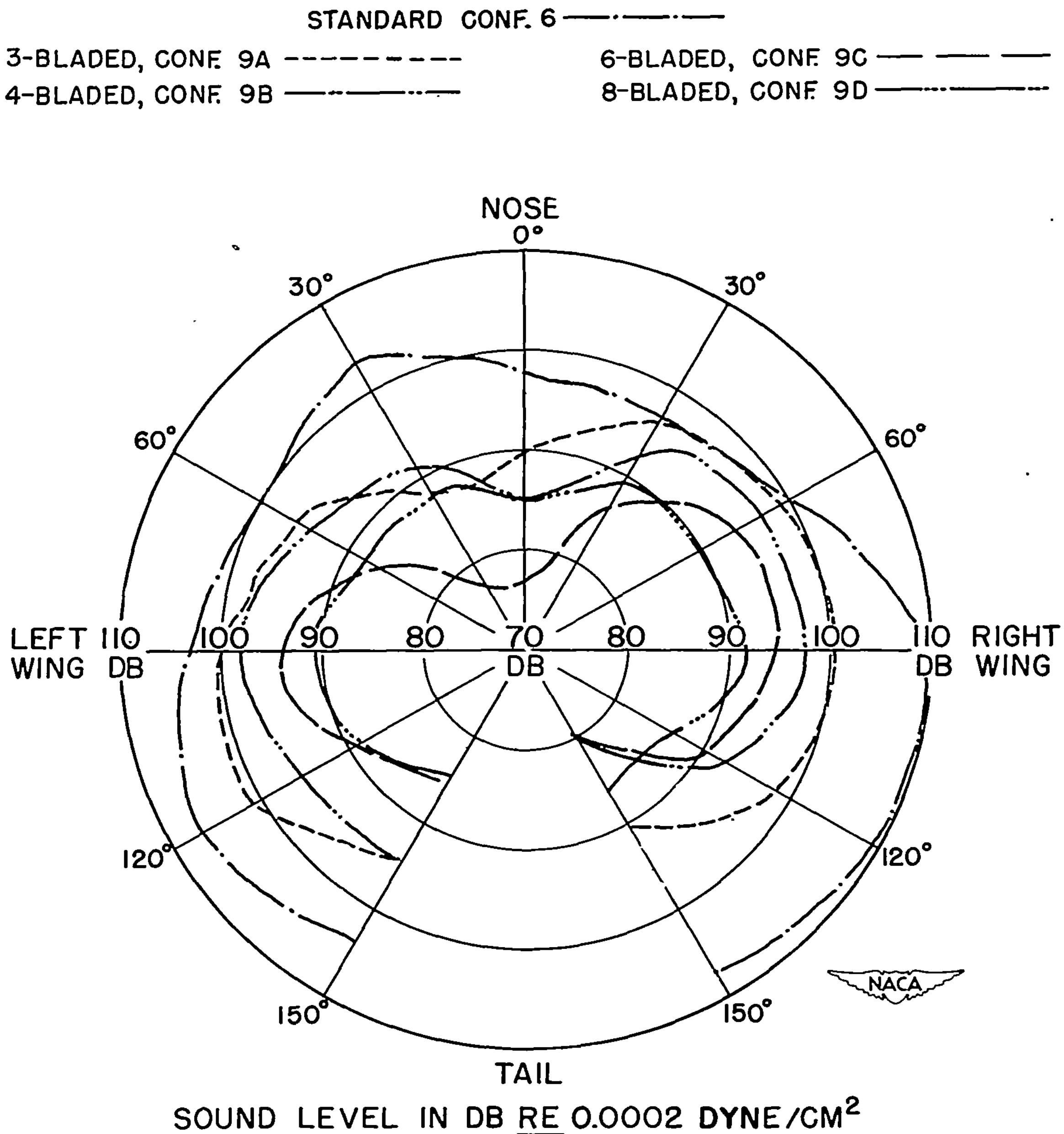
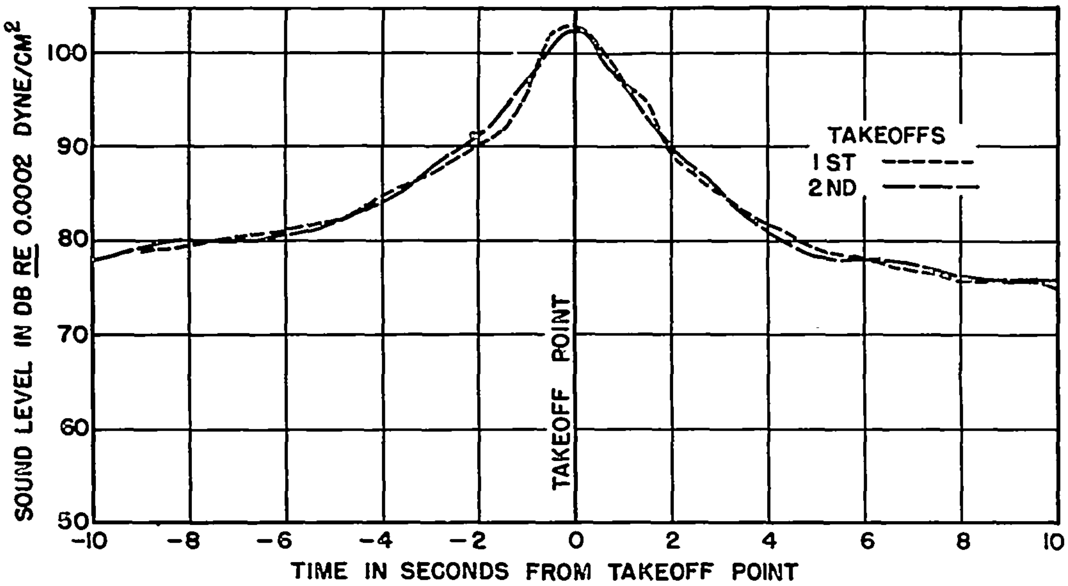
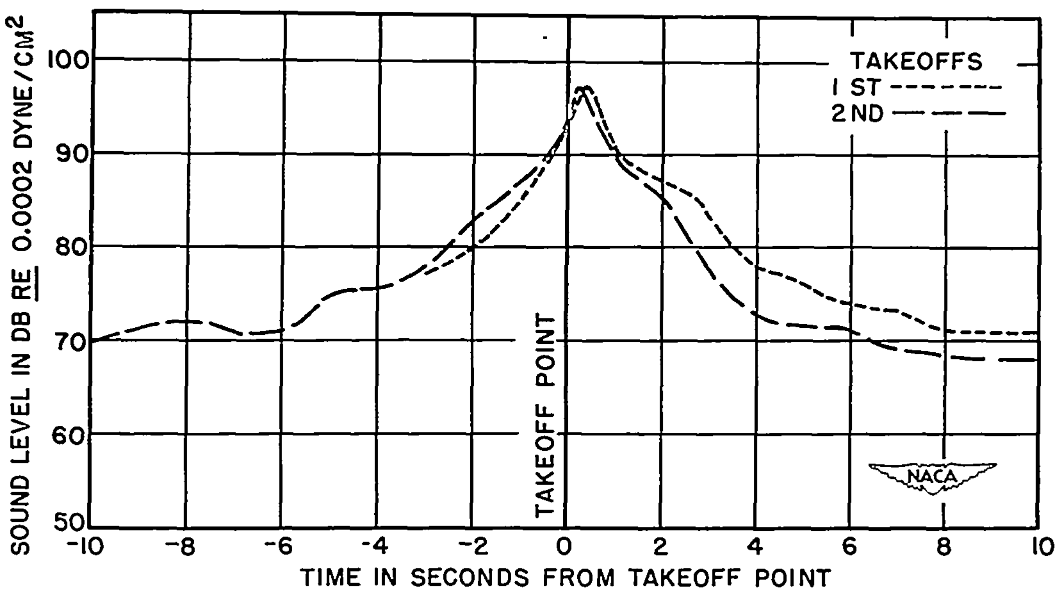


Figure 30.- Comparison of propeller fundamentals for configurations of series A from frequency analysis on ground 50 feet from hub. Flat weighting. Refer to table II for engine powers, tip speeds, and propeller diameters. RE indicates "referred to a level of."



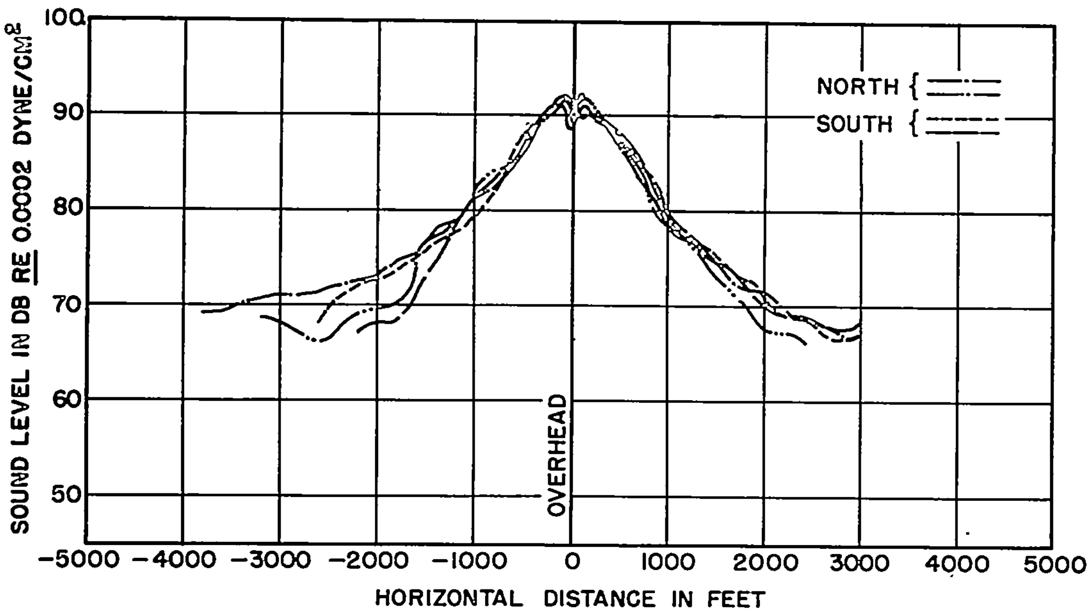
Configuration 8; 2500 rpm.



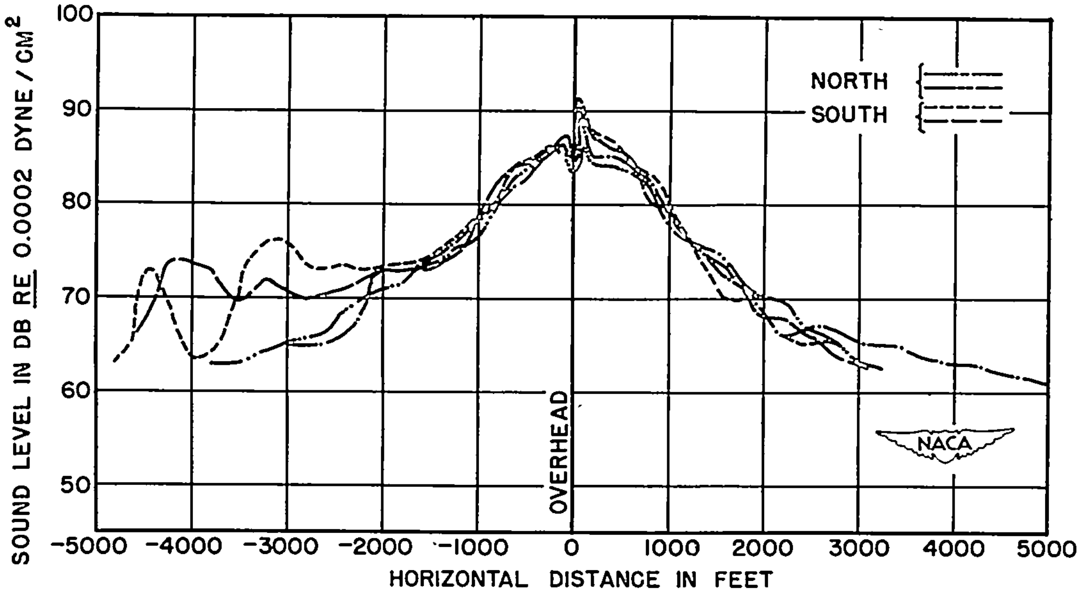
Configuration 9B; 2500 rpm.

(a) Take-offs. Flat weighting; airplane leaving ground as it passes 50 feet from microphone.

Figure 31.- Comparison of take-off measurements and of flight measurements at 100-foot altitude for configurations of series B. Refer to table II for engine powers, tip speeds, and propeller diameters. RE indicates "referred to a level of."



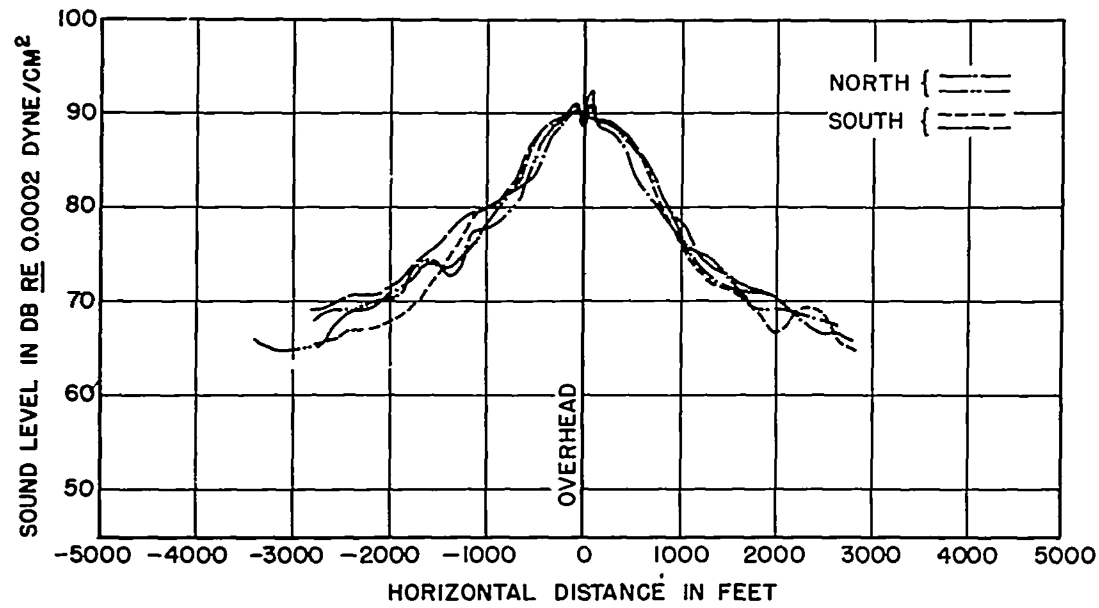
Configuration 8; 2500 rpm; wind - west, 1 mph.



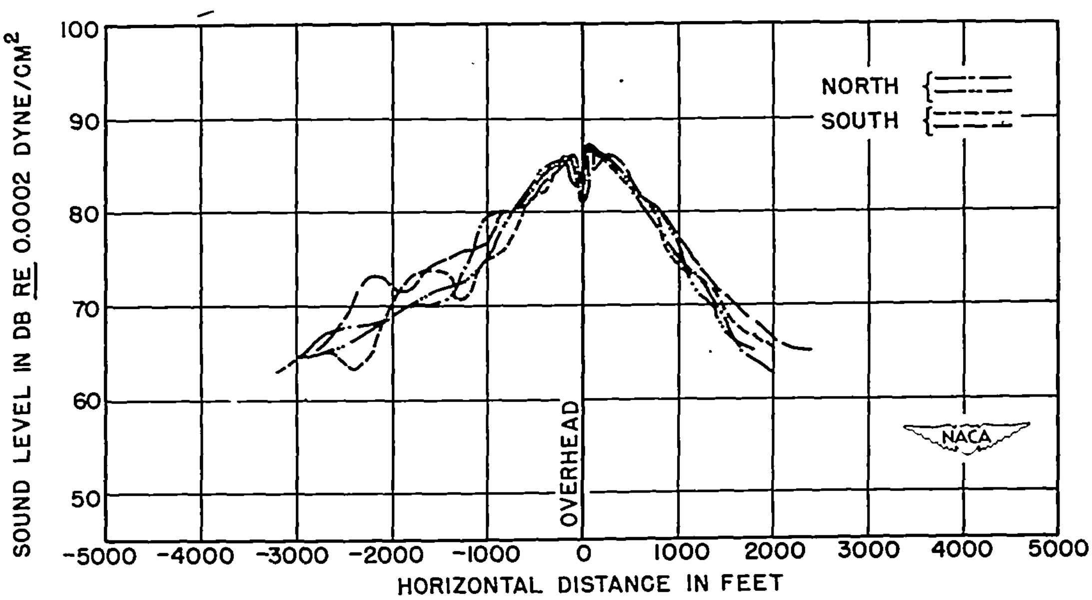
Configuration 9B; 2500 rpm; wind - west, 1 mph.

(b) Flights at 100-foot altitude. Maximum power; flat weighting; airplane passing overhead.

Figure 31.- Continued.



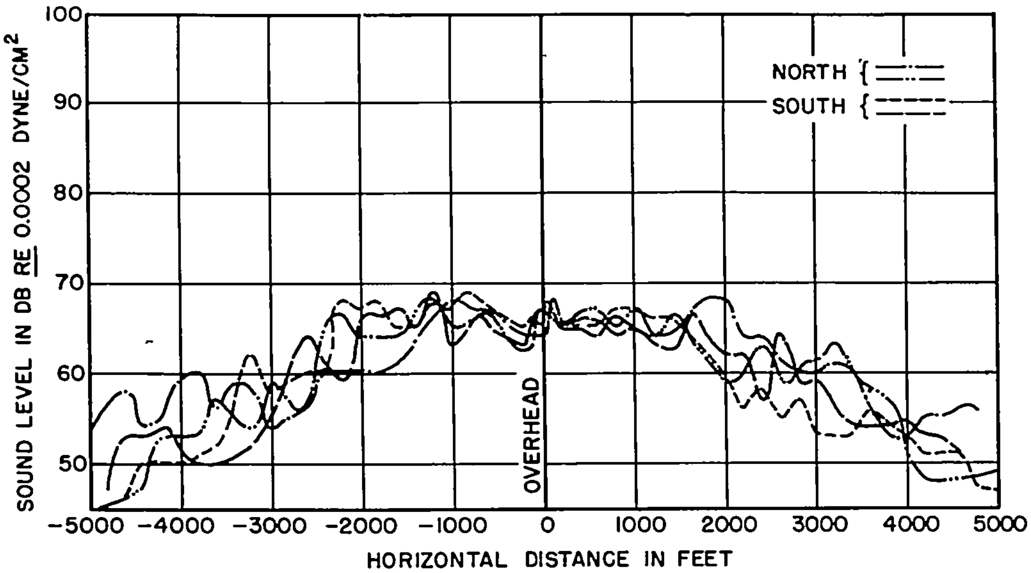
Configuration 8; 2250 rpm; wind - west, 1 mph.



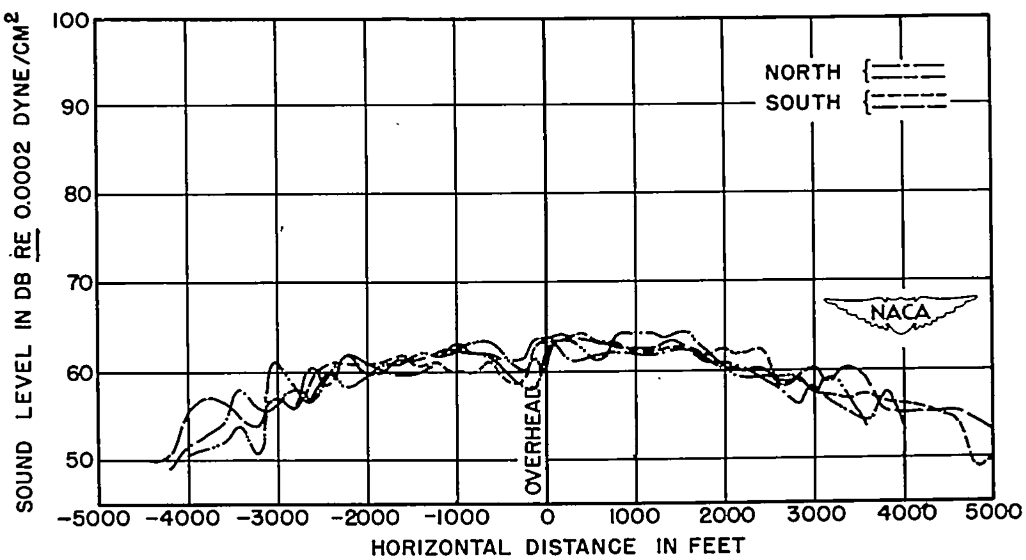
Configuration 9B; 2250 rpm; wind - 0 mph.

(c) Flights at 100-foot altitude. Cruising power; flat weighting; airplane passing overhead.

Figure 31.- Concluded.



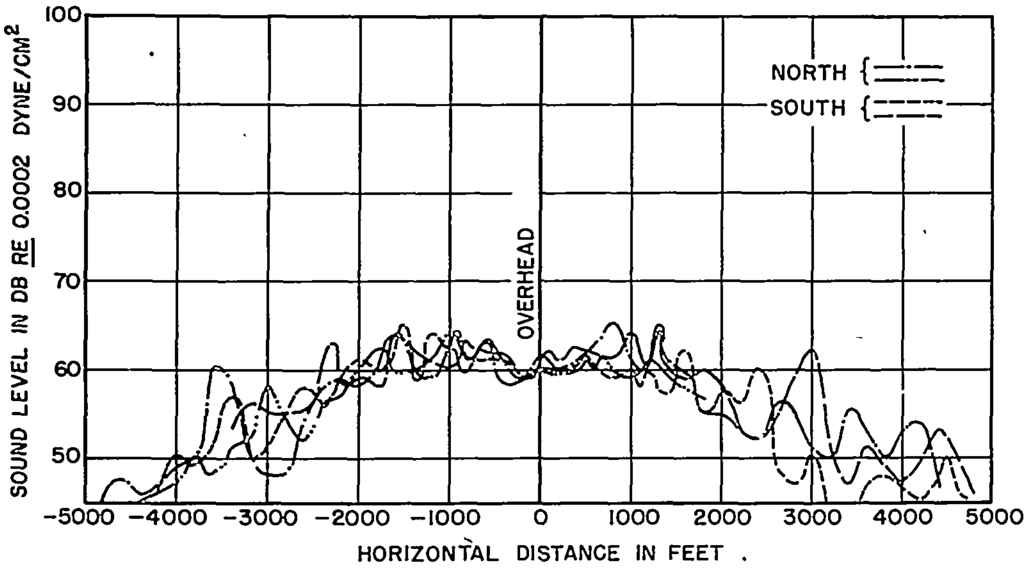
Configuration 8; 2500 rpm; wind - southwest, 3 mph.



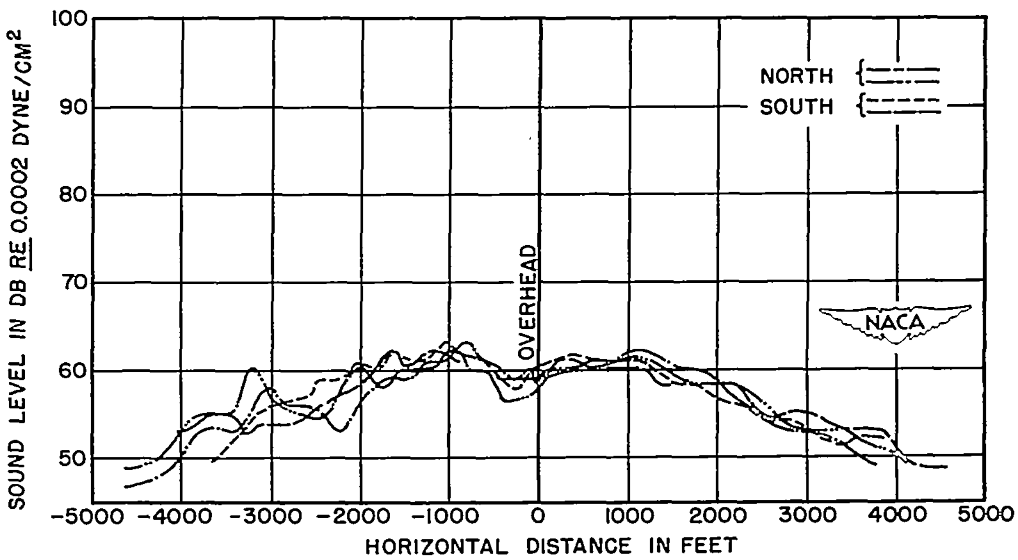
Configuration 9B; 2500 rpm; wind - east, 3 mph.

(a) Flights at 500-foot altitude. Maximum power; 40-decibel weighting; airplane passing overhead.

Figure 32.- Comparison of flight measurements at 500-foot altitude and of ground analyses for configurations of series B. Refer to table II for engine powers, tip speeds, and propeller diameters. RE indicates "referred to a level of."



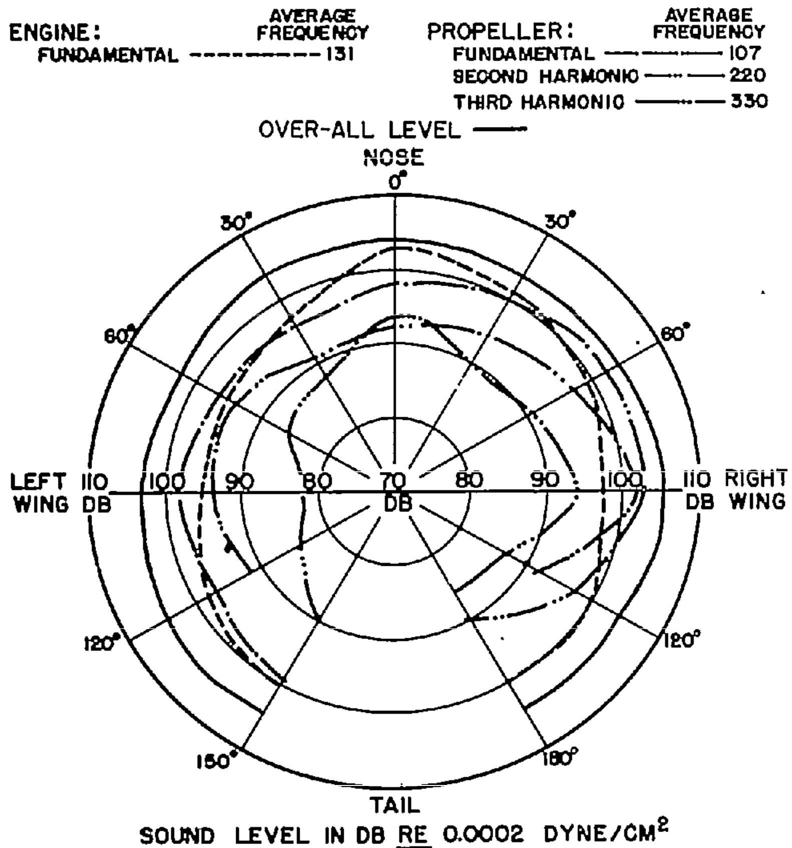
Configuration 8; 2250 rpm; wind - southwest, 4 mph.



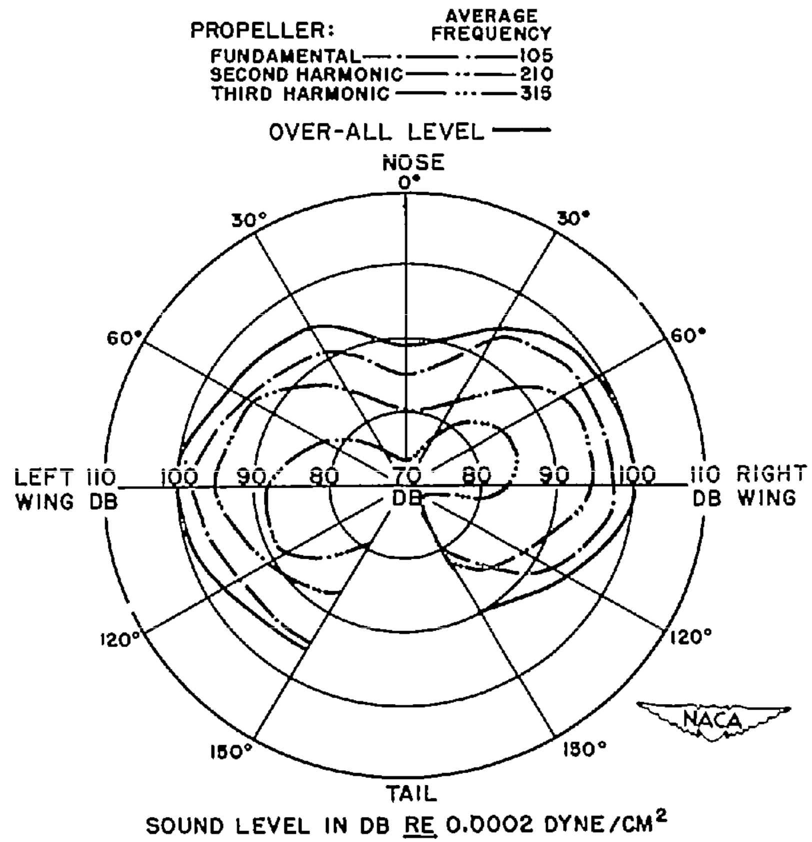
Configuration 9B; 2250 rpm; wind - east, 3 mph.

(b) Flights at 500-foot altitude. Cruising power; 40-decibel weighting; airplane passing overhead.

Figure 32.- Continued.



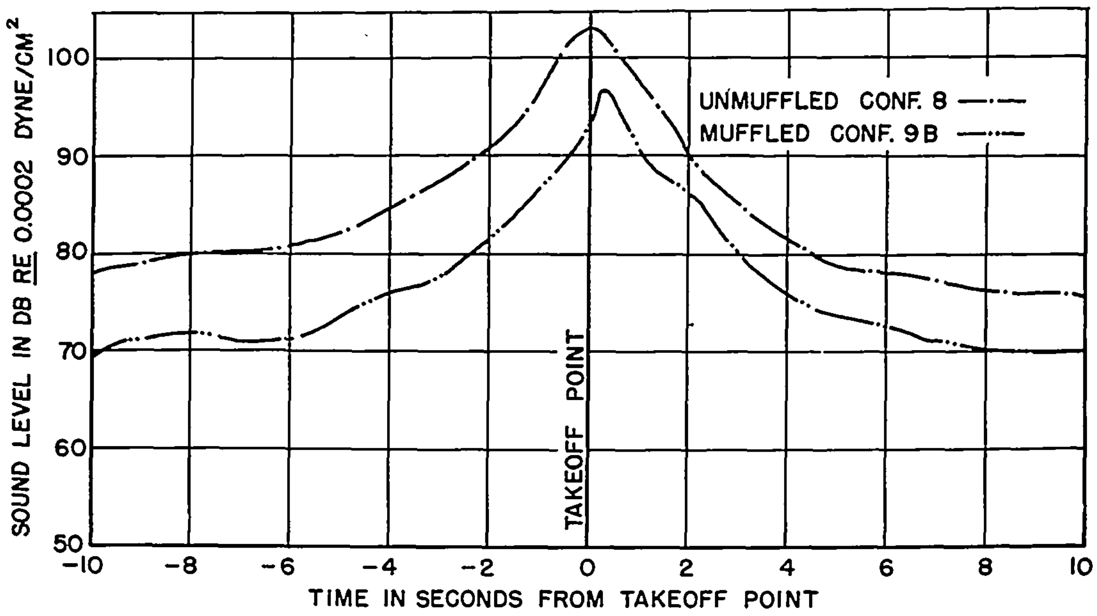
Configuration 8; 2500 rpm.



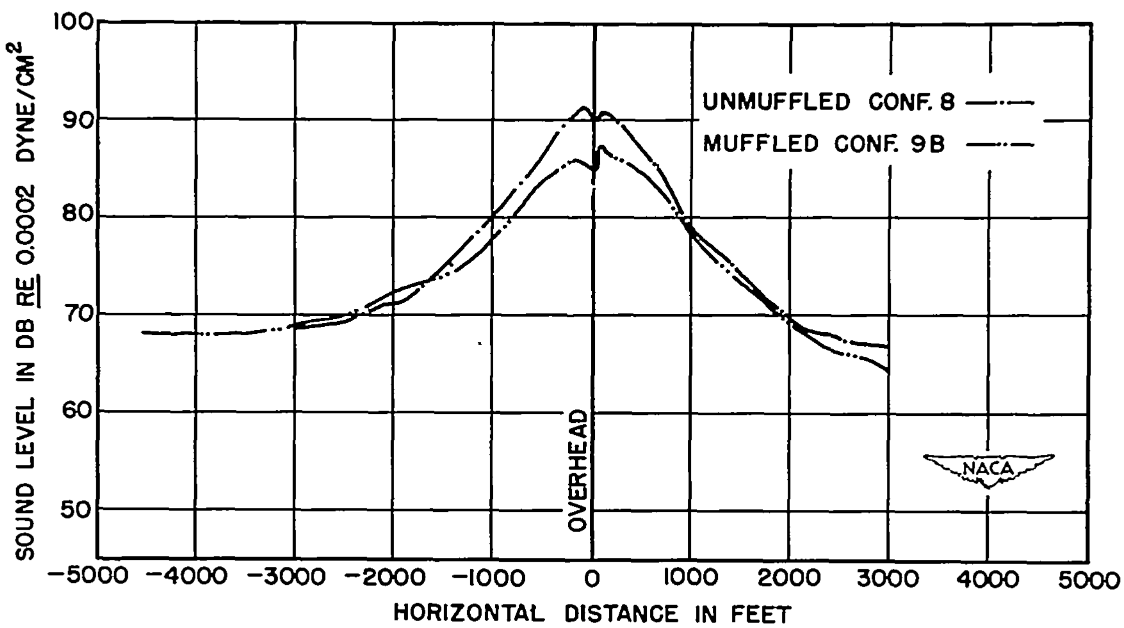
Configuration 9B; 2475 rpm; engine noise masked by propeller.

(c) Frequency analysis on ground 50 feet from hub. Flat weighting.

Figure 32.- Concluded.

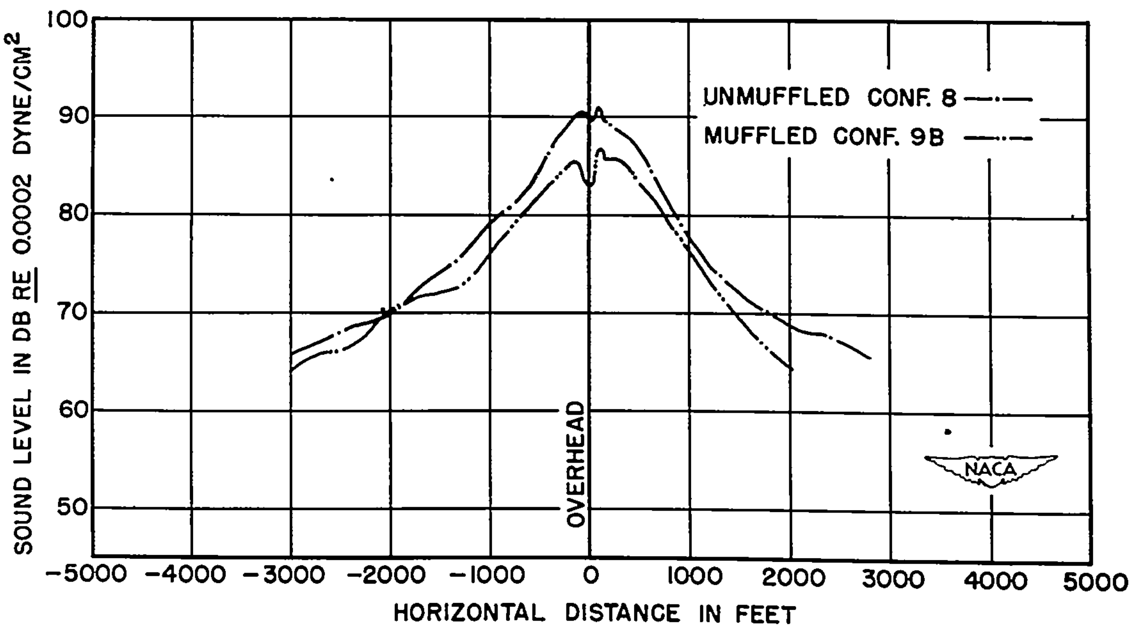


(a) Averages of take-offs. Flat weighting; airplane leaving ground as it passes 50 feet from microphone.



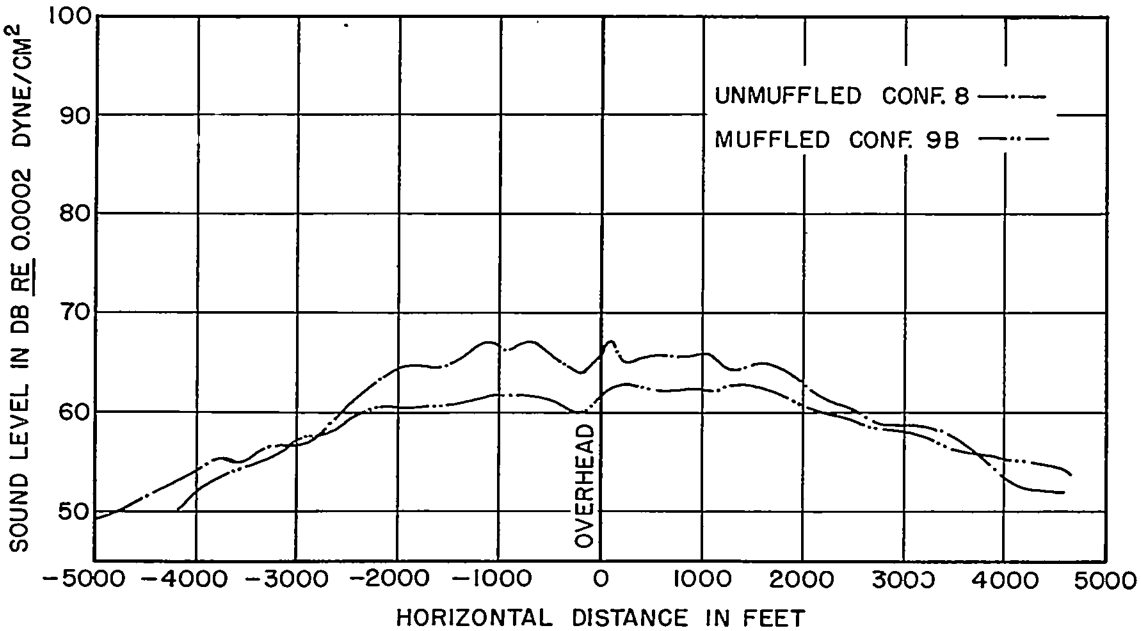
(b) Averages of flights at 100-foot altitude. Maximum power; flat weighting; airplane passing overhead.

Figure 33.- Average curves of take-offs and of flights at 100-foot altitude for configurations of series B. Refer to table II for engine powers, tip speeds, and propeller diameters. RE indicates "referred to a level of."

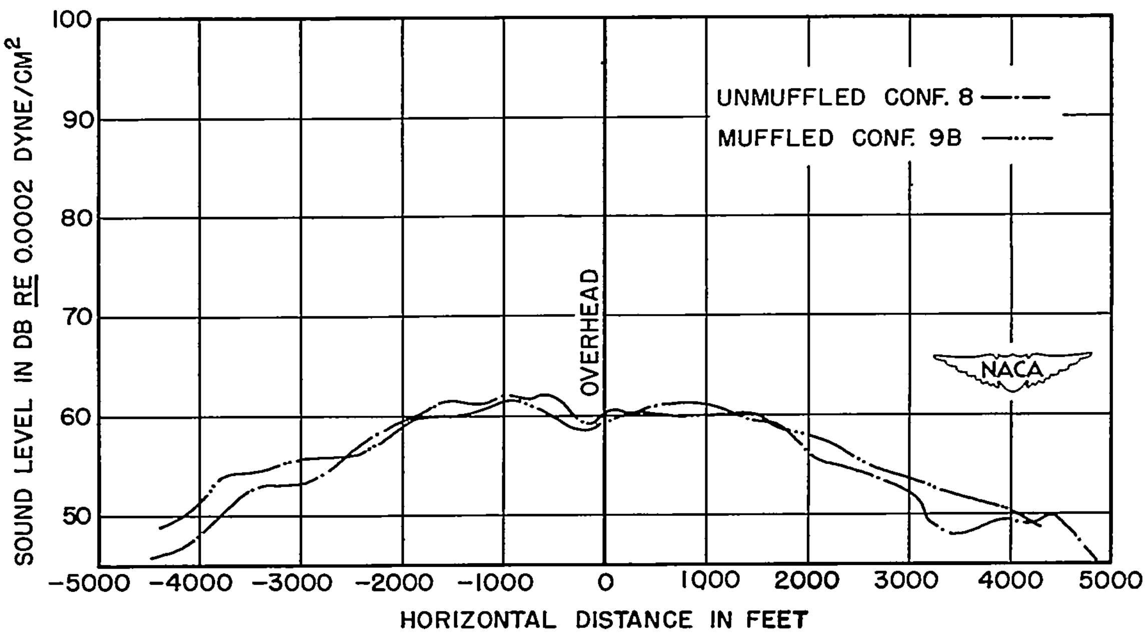


(c) Averages of flights at 100-foot altitude. Cruising power; flat weighting; airplane passing overhead.

Figure 33.- Concluded.

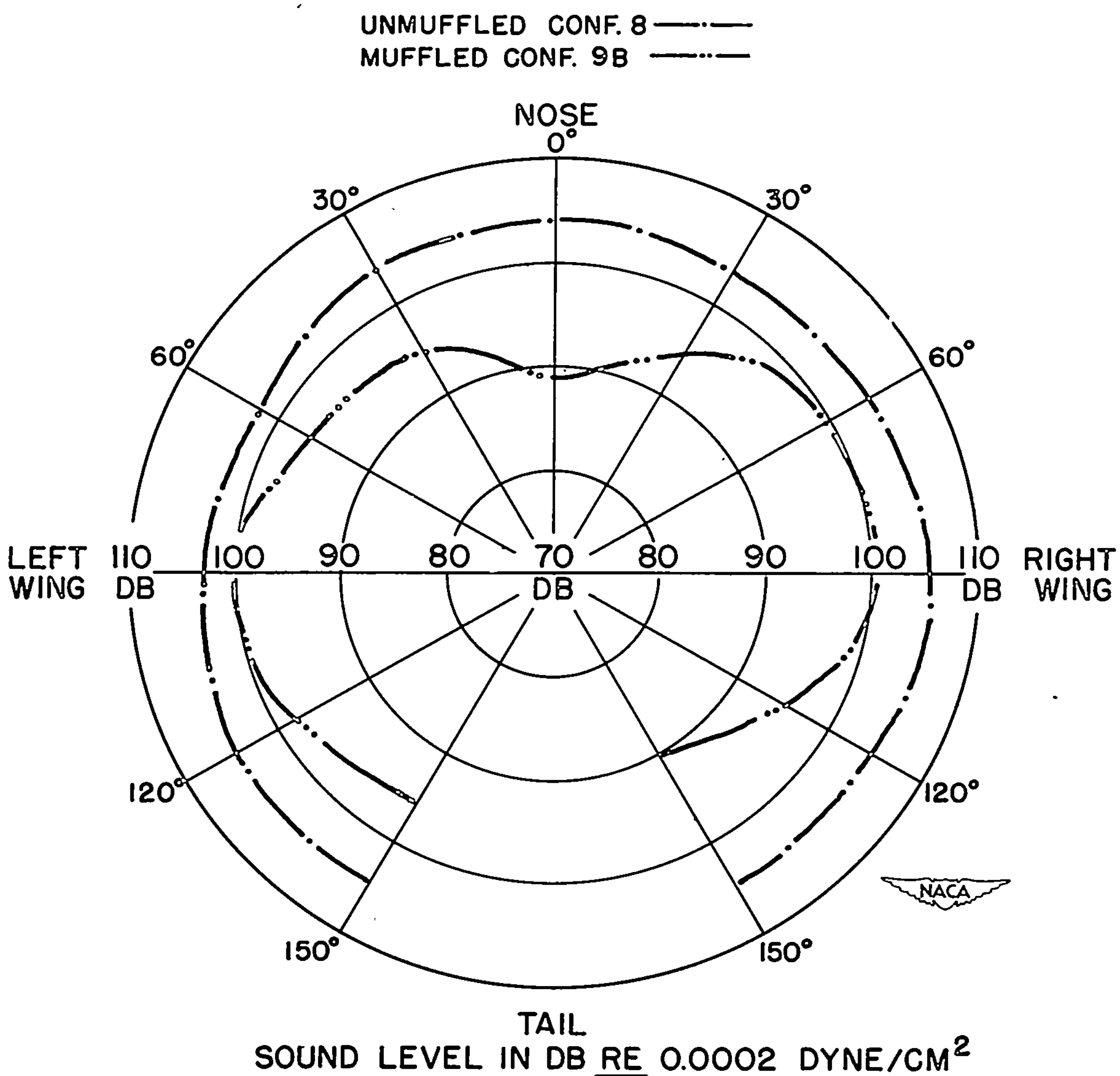


(a) Maximum power.



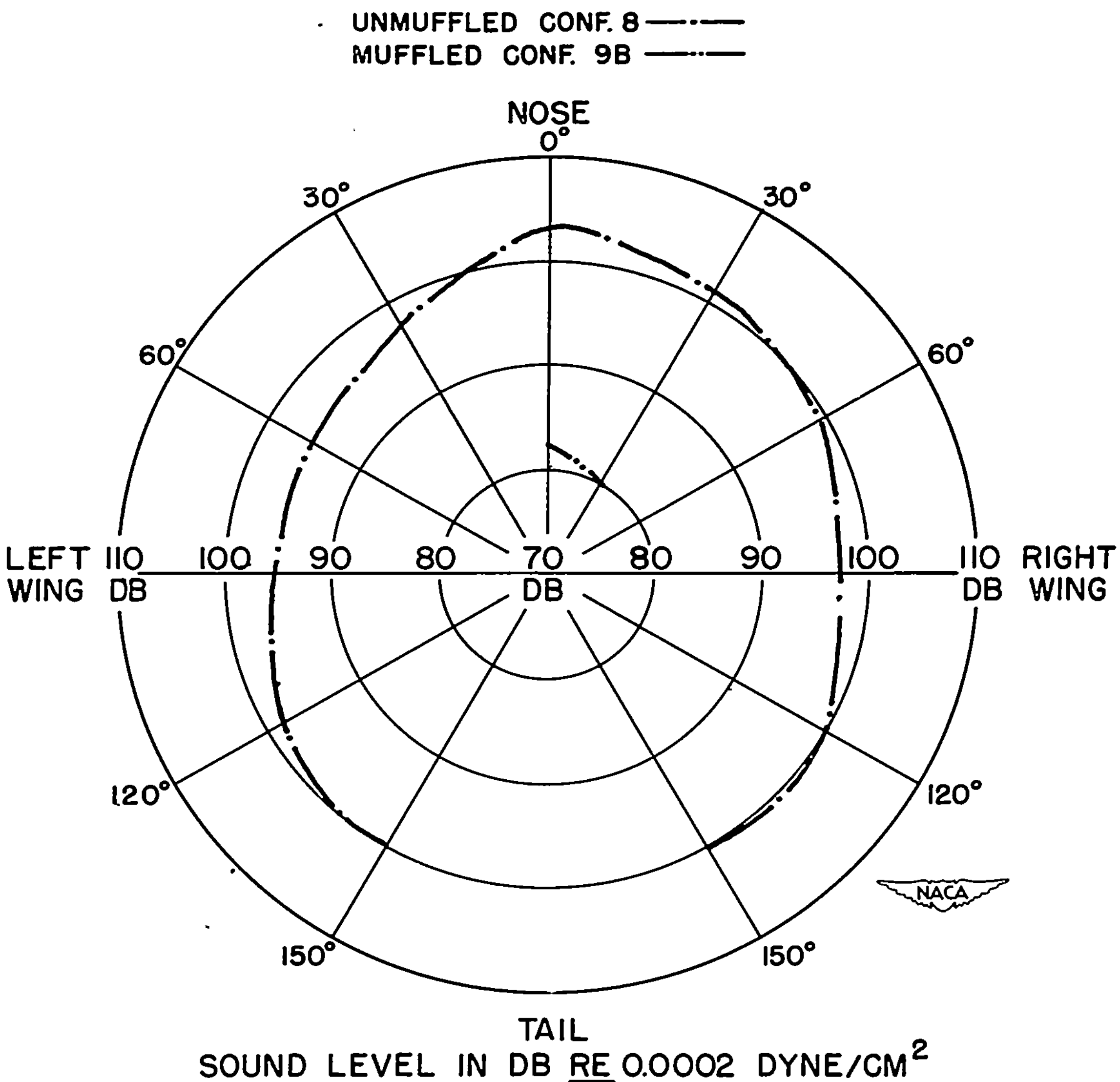
(b) Cruising power.

Figure 34.- Average curves of flights at 500-foot altitude for configurations of series B. 40-decibel weighting; airplane passing overhead. Refer to table II for engine powers, tip speeds, and propeller diameters. RE indicates "referred to a level of."



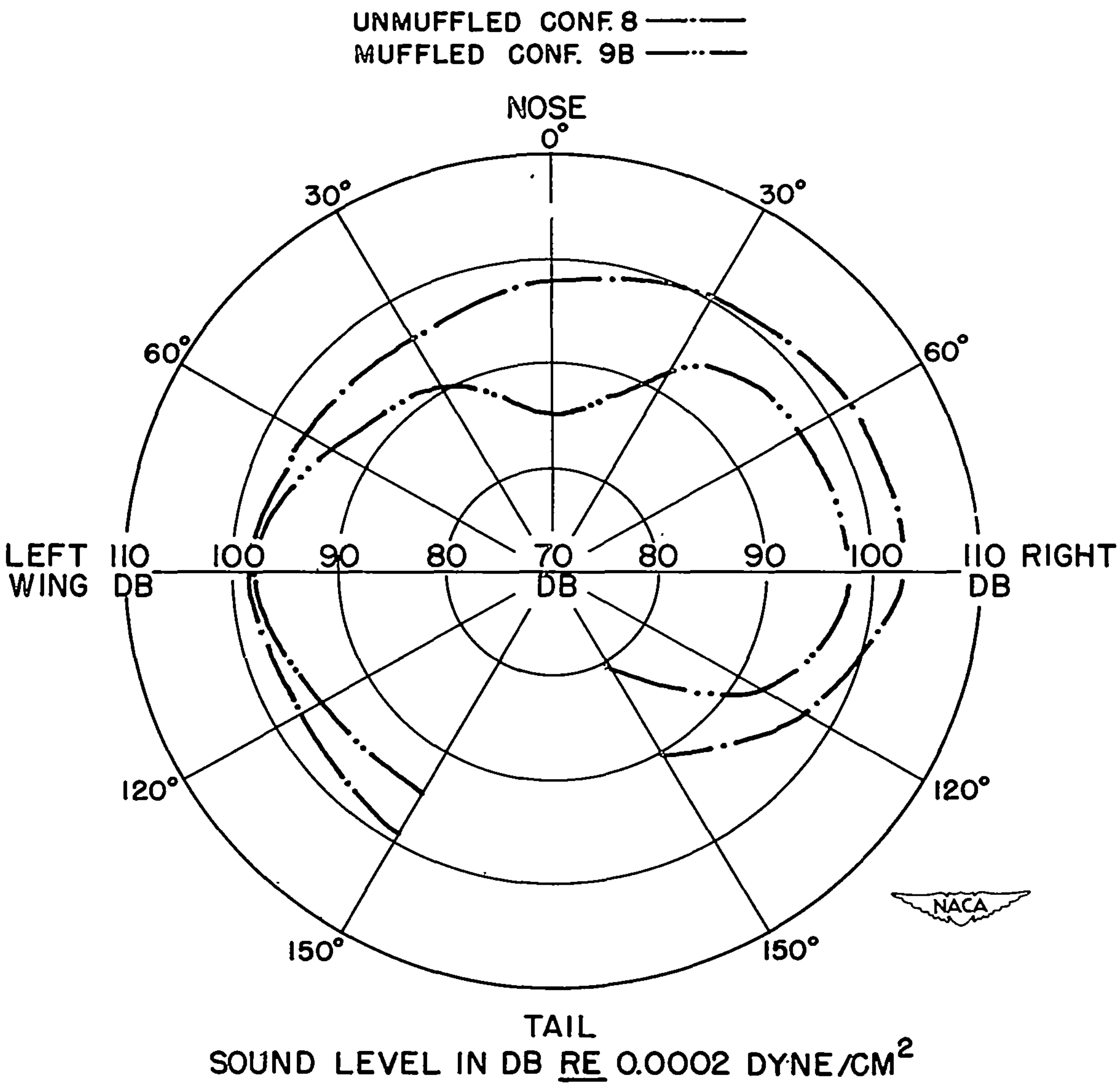
(a) Over-all levels.

Figure 35.- Comparisons of over-all levels, engine fundamentals, and propeller fundamentals from frequency analyses on ground 50 feet from hub for configurations of series B. Flat weighting. Refer to table II for engine powers, tip speeds, and propeller diameters. RE indicates "referred to a level of."



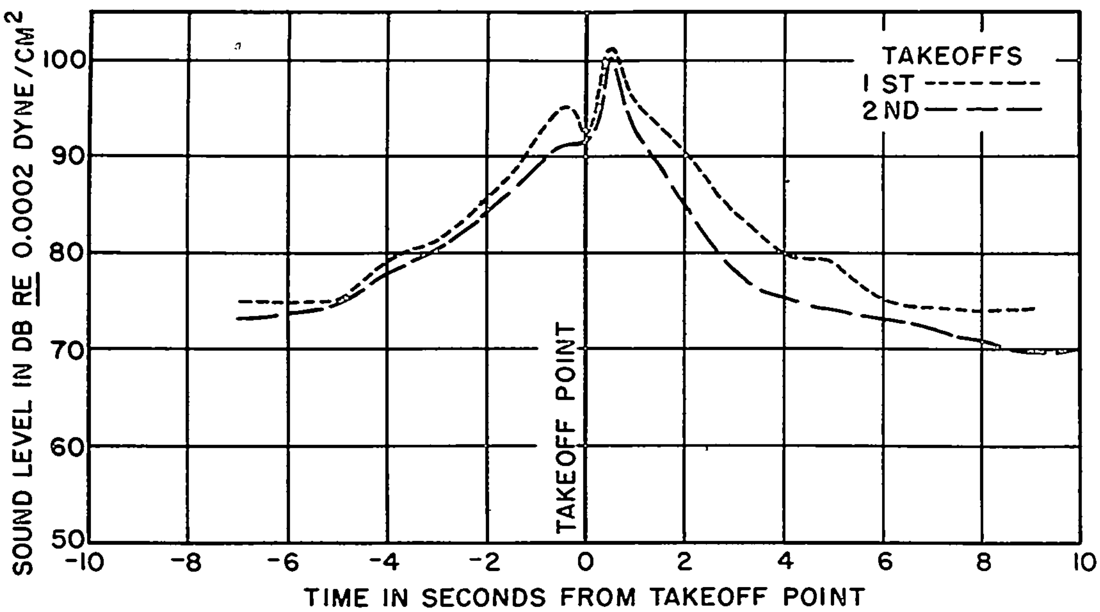
(b) Engine fundamentals.

Figure 35.- Continued.

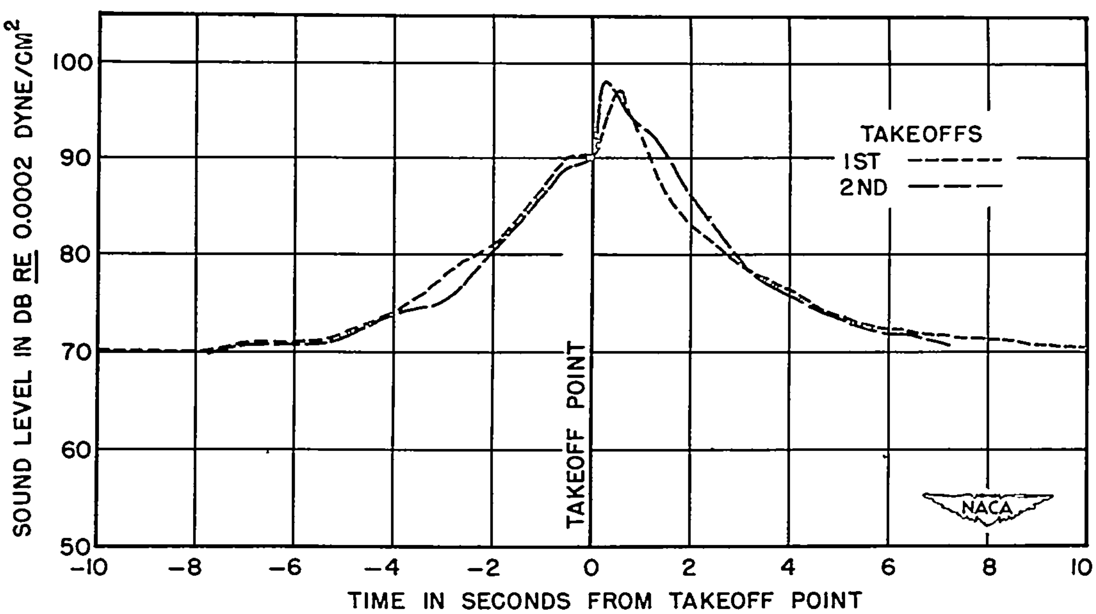


(c) Propeller fundamentals.

Figure 35.- Concluded.



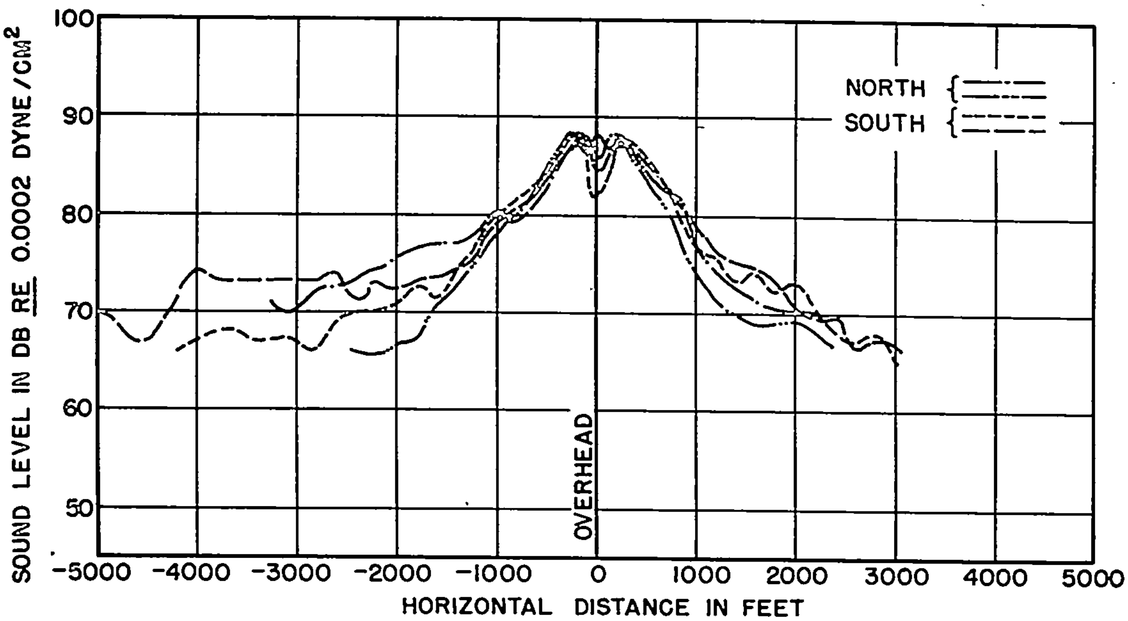
Configuration 9D; 2500 rpm.



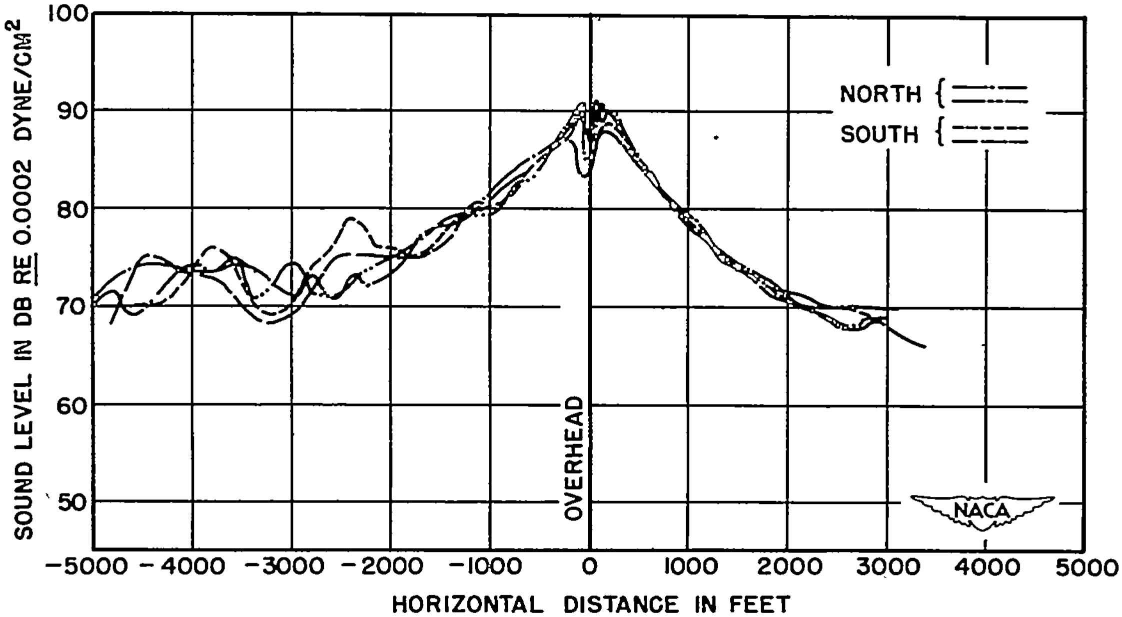
Configuration 10; 2500 rpm.

(a) Take-offs. Flat weighting; airplane leaving ground as it passes 50 feet from microphone.

Figure 36.- Comparison of take-off measurements and of flight measurements at 100-foot altitude for configurations of series C. Refer to table II for engine powers, tip speeds, and propeller diameters. RE indicates "referred to a level of."



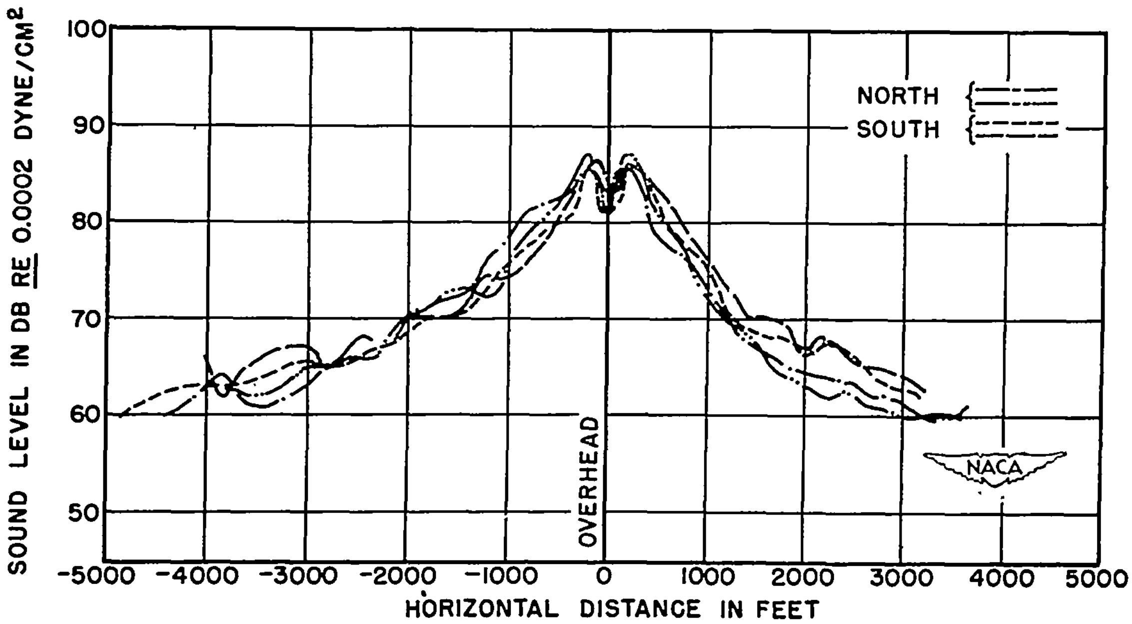
Configuration 9D; 2500 rpm; wind - west, 2 mph.



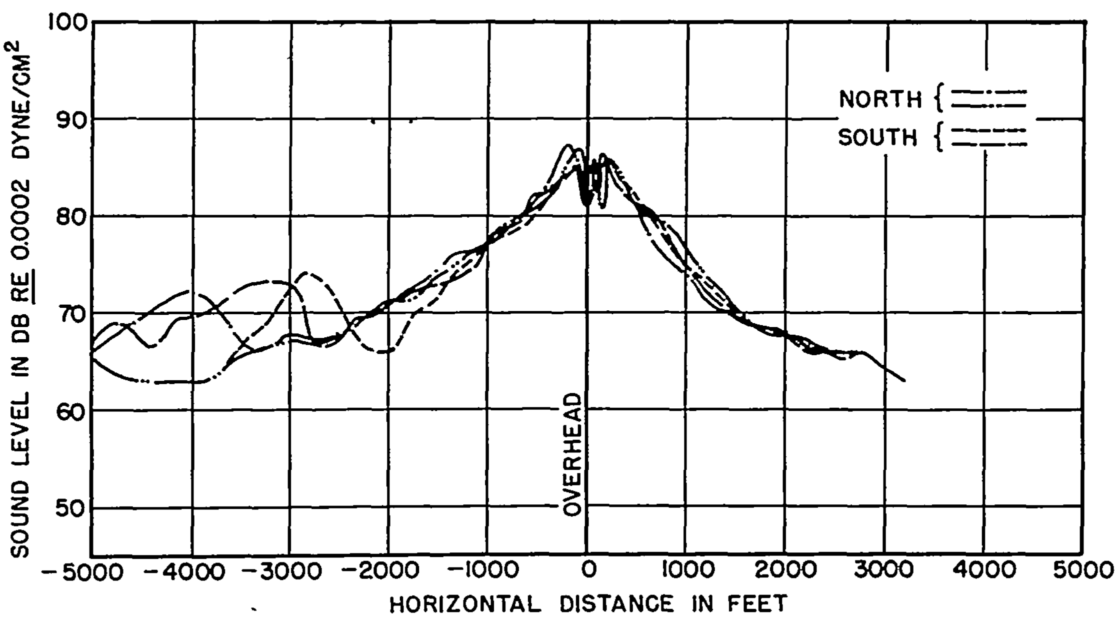
Configuration 10; 2250 rpm; wind - 0 mph.

(b) Flights at 100-foot altitude. Maximum power; flat weighting; airplane passing overhead.

Figure 36.- Continued.



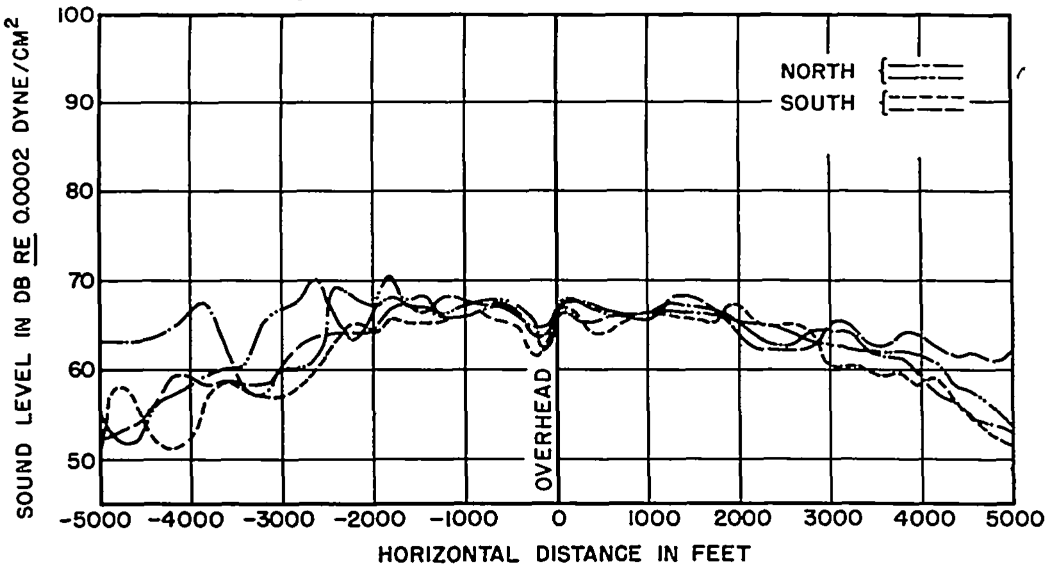
Configuration 9D; 2250 rpm; wind - west, 2 mph.



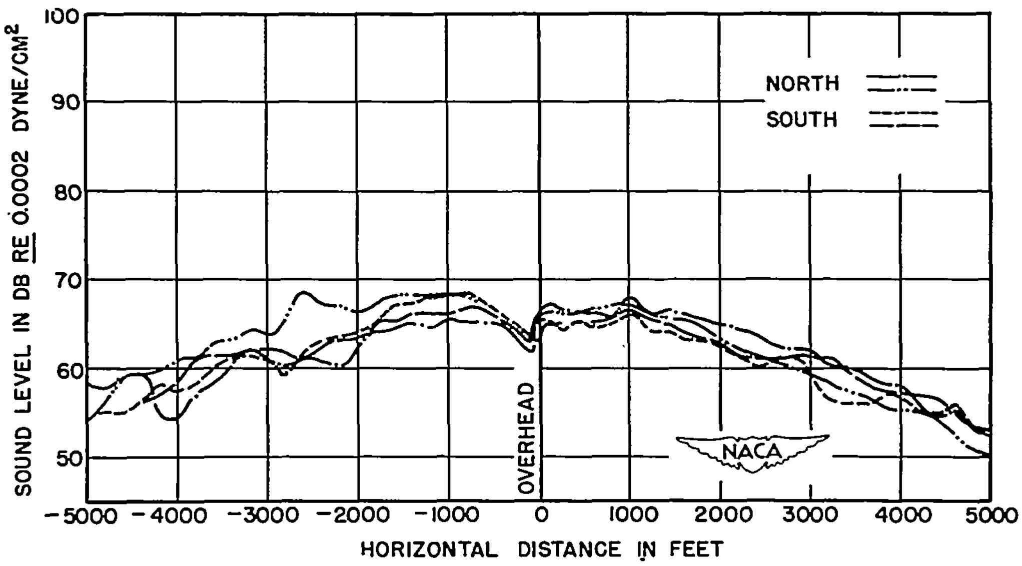
Configuration 10; 2250 rpm; wind - west, 1 mph.

(c) Flights at 100-foot altitude. Cruising power; flat weighting; airplane passing overhead.

Figure 36.- Concluded.



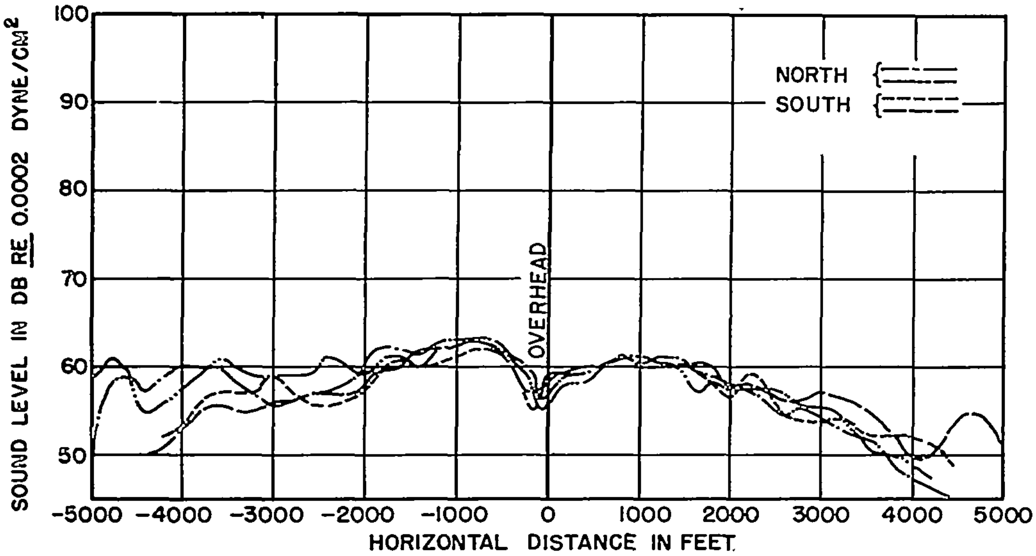
Configuration 9D; 2500 rpm; wind - east, 1 mph.



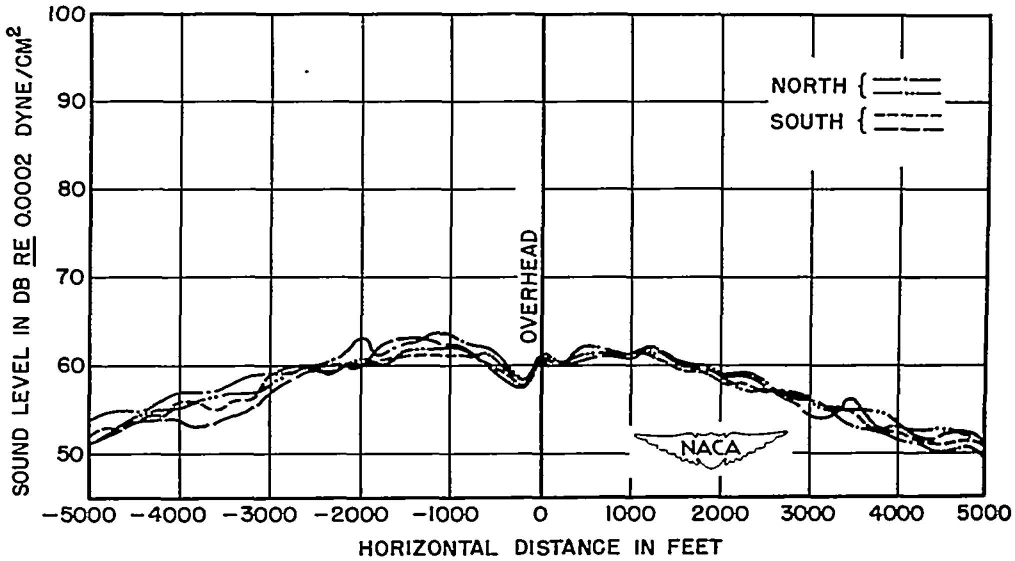
Configuration 10; 2500 rpm; wind - west, 1 mph.

(a) Flights at 500-foot altitude. Maximum power; 40-decibel weighting; airplane passing overhead.

Figure 37.- Comparison of flight measurements at 500-foot altitude and of ground analyses for configurations of series C. Refer to table II for engine powers, tip speeds, and propeller diameters. RE indicates "referred to a level of."



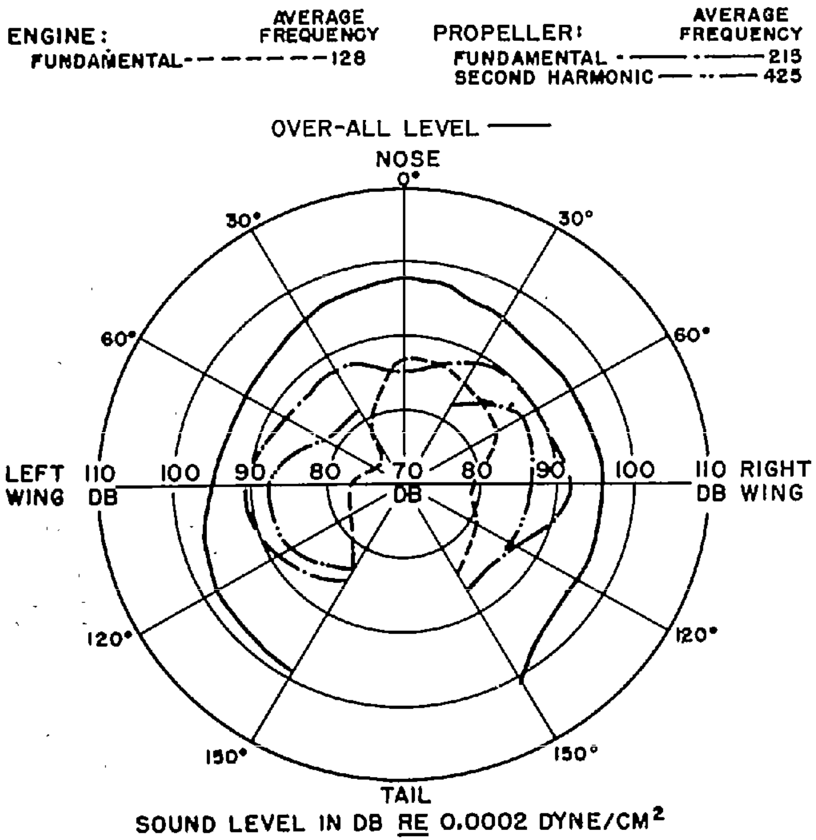
Configuration 9D; 2250 rpm; wind - east, 1 mph.



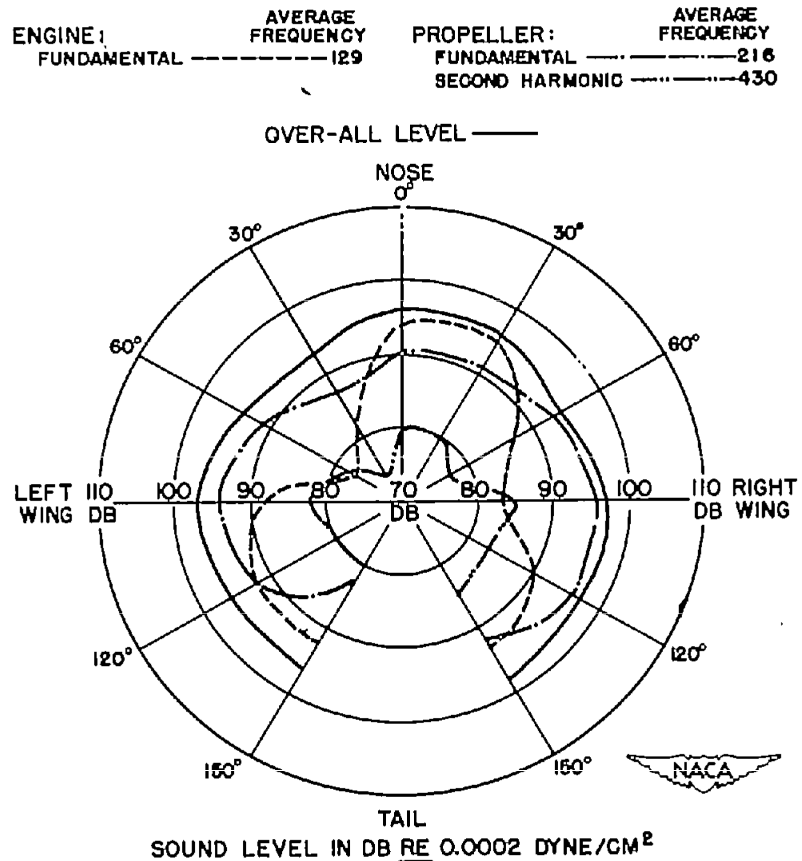
Configuration 10; 2250 rpm; wind - west, 1 mph.

(b) Flights at 500-foot altitude. Cruising power; 40-decibel weighting; airplane passing overhead.

Figure 37.- Continued.



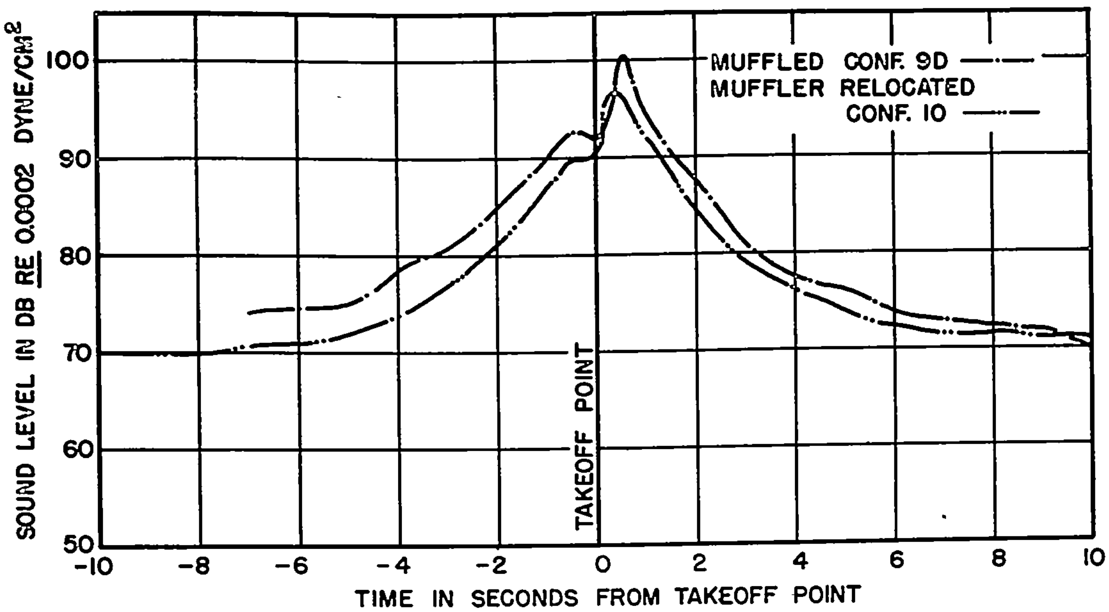
Configuration 9D; 2500 rpm.



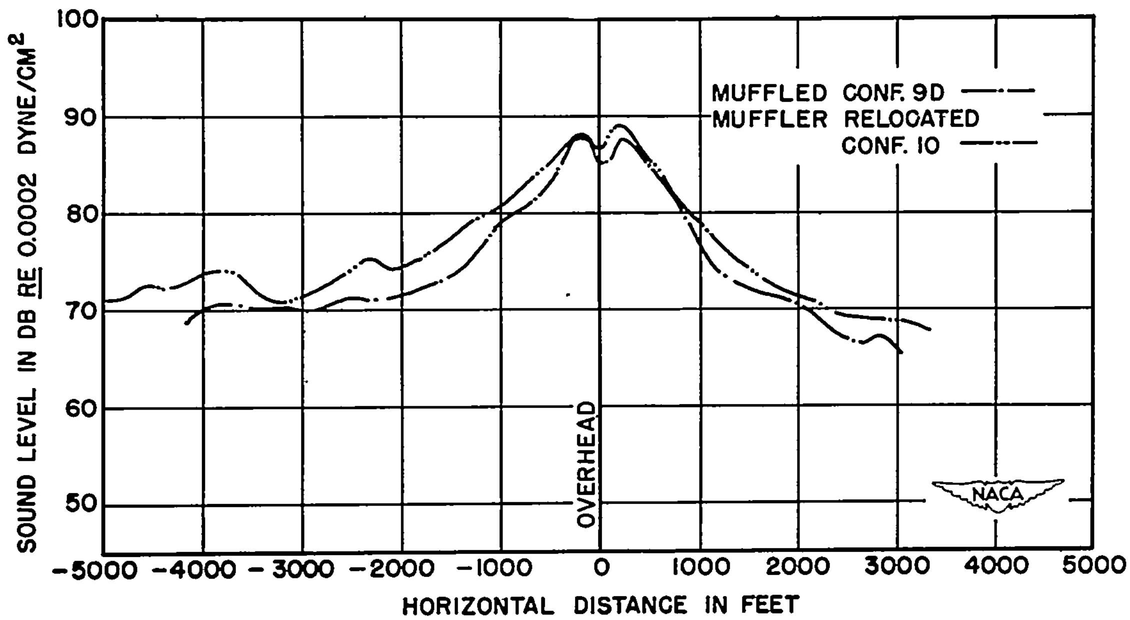
Configuration 10; 2500 rpm.

(c) Frequency analysis on ground 50 feet from hub. Flat weighting.

Figure 37.- Concluded.

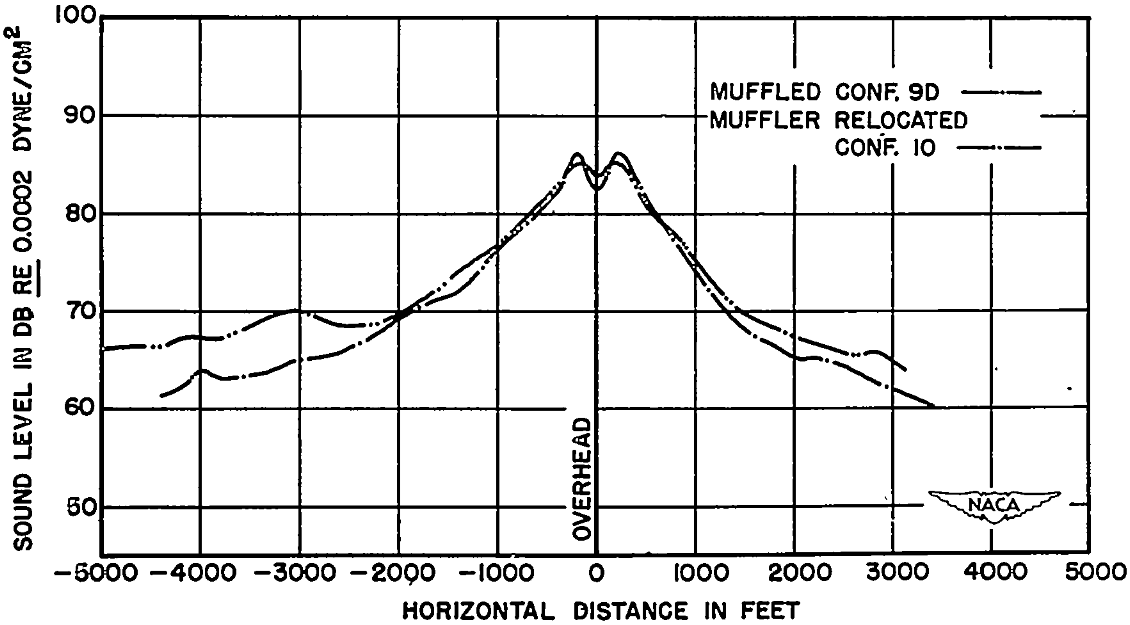


(a) Averages of take-offs. Flat weighting; airplane leaving ground as it passes 50 feet from microphone.



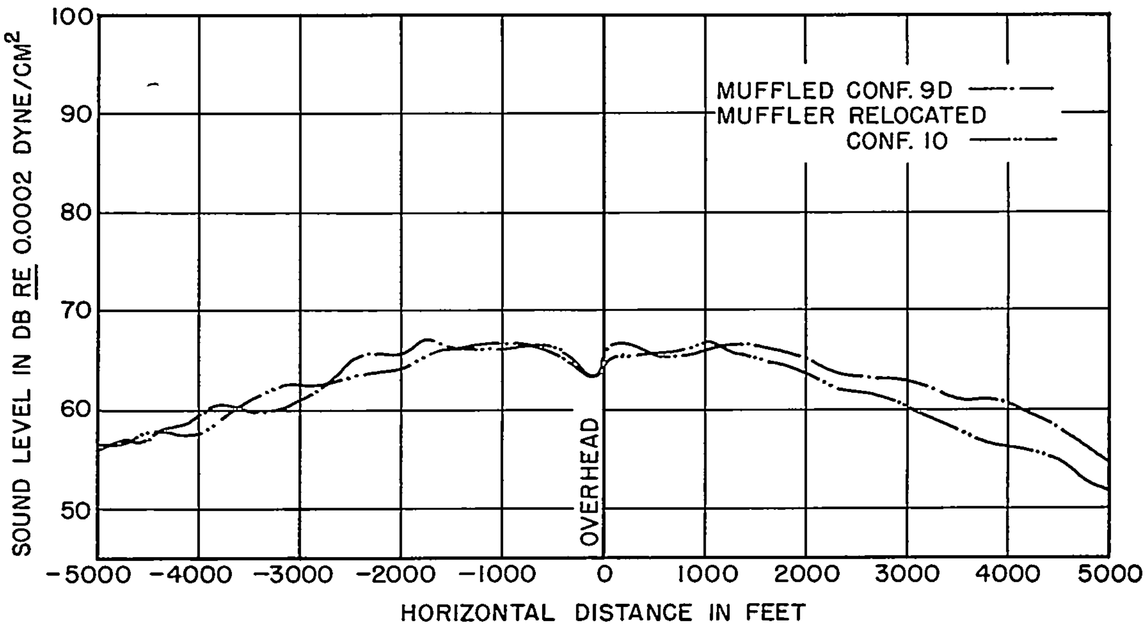
(b) Averages of flights at 100-foot altitude. Maximum power; flat weighting; airplane passing overhead.

Figure 38.- Average curves of take-offs and of flights at 100-foot altitude for configurations of series C. Refer to table II for engine powers, tip speeds, and propeller diameters. RE indicates "referred to a level of."

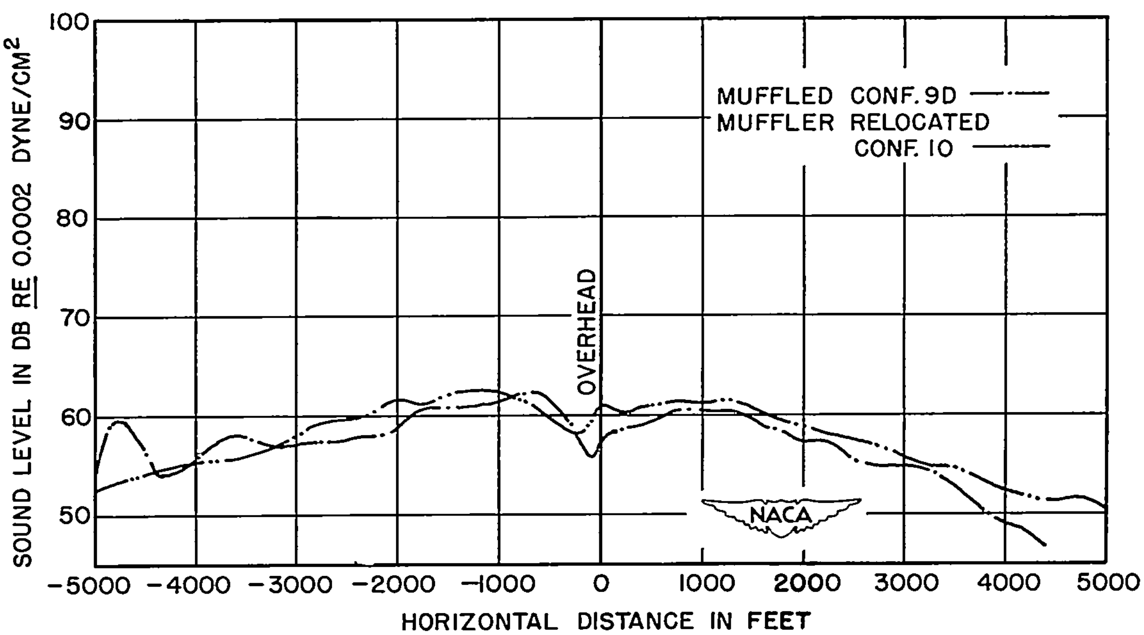


(c) Averages of flights at 100-foot altitude. Cruising power; flat weighting; airplane passing overhead.

Figure 38.- Concluded.

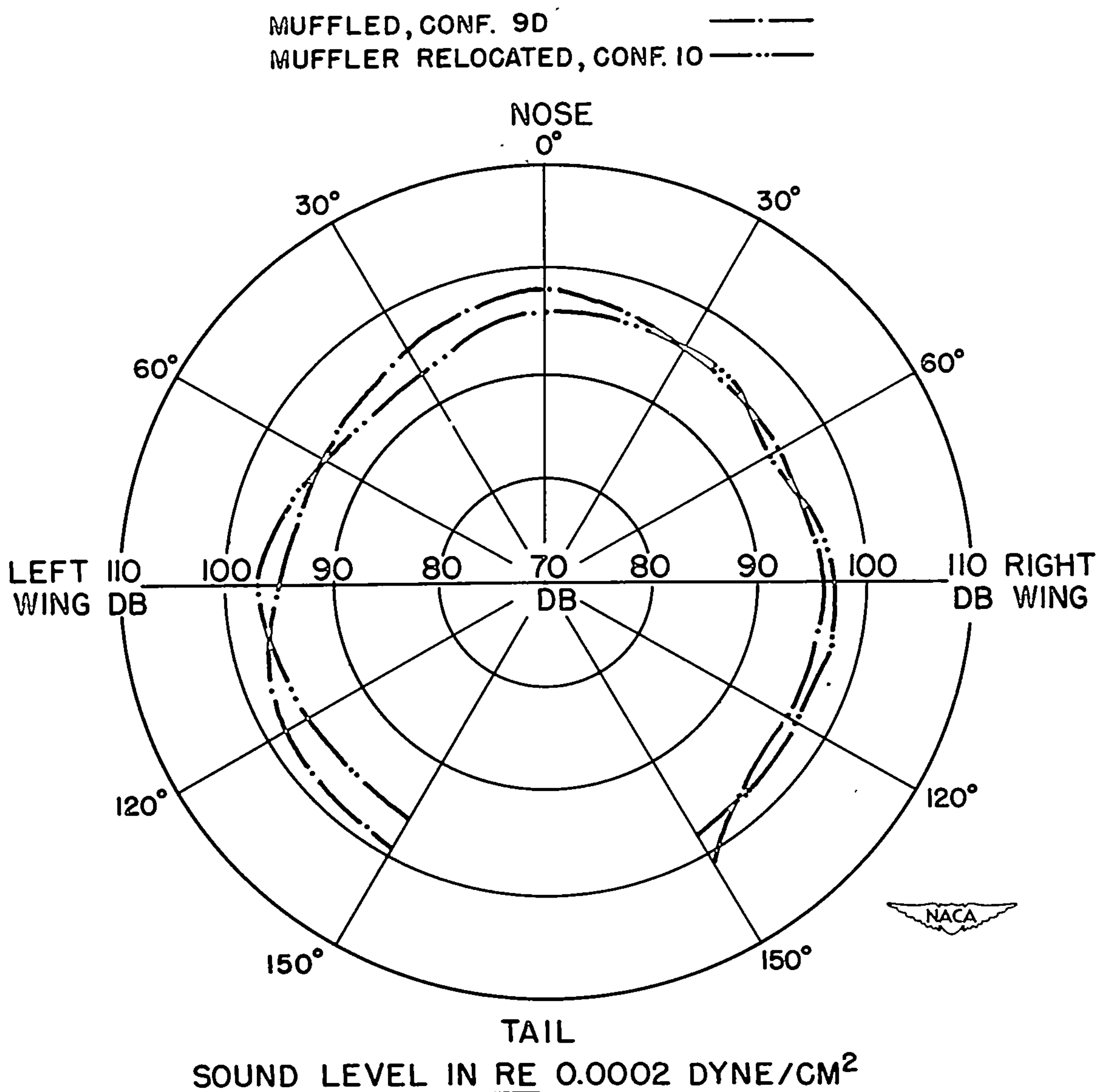


(a) Maximum power.



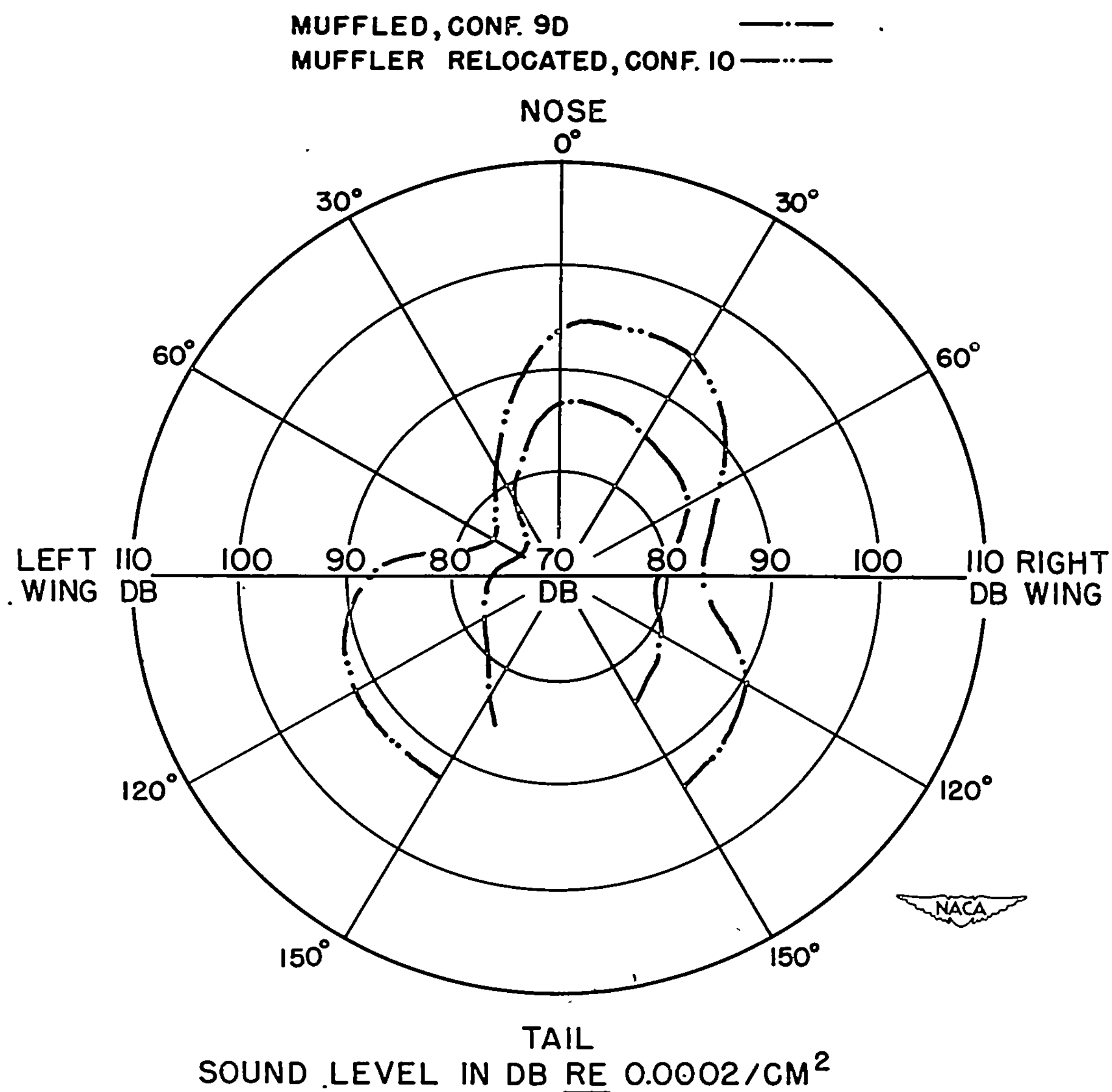
(b) Cruising power.

Figure 39.- Average curves of flights at 500-foot altitude for configurations of series C. 40-decibel weighting; airplane passing overhead. Refer to table II for engine powers, tip speeds, and propeller diameters. RE indicates "referred to a level of."



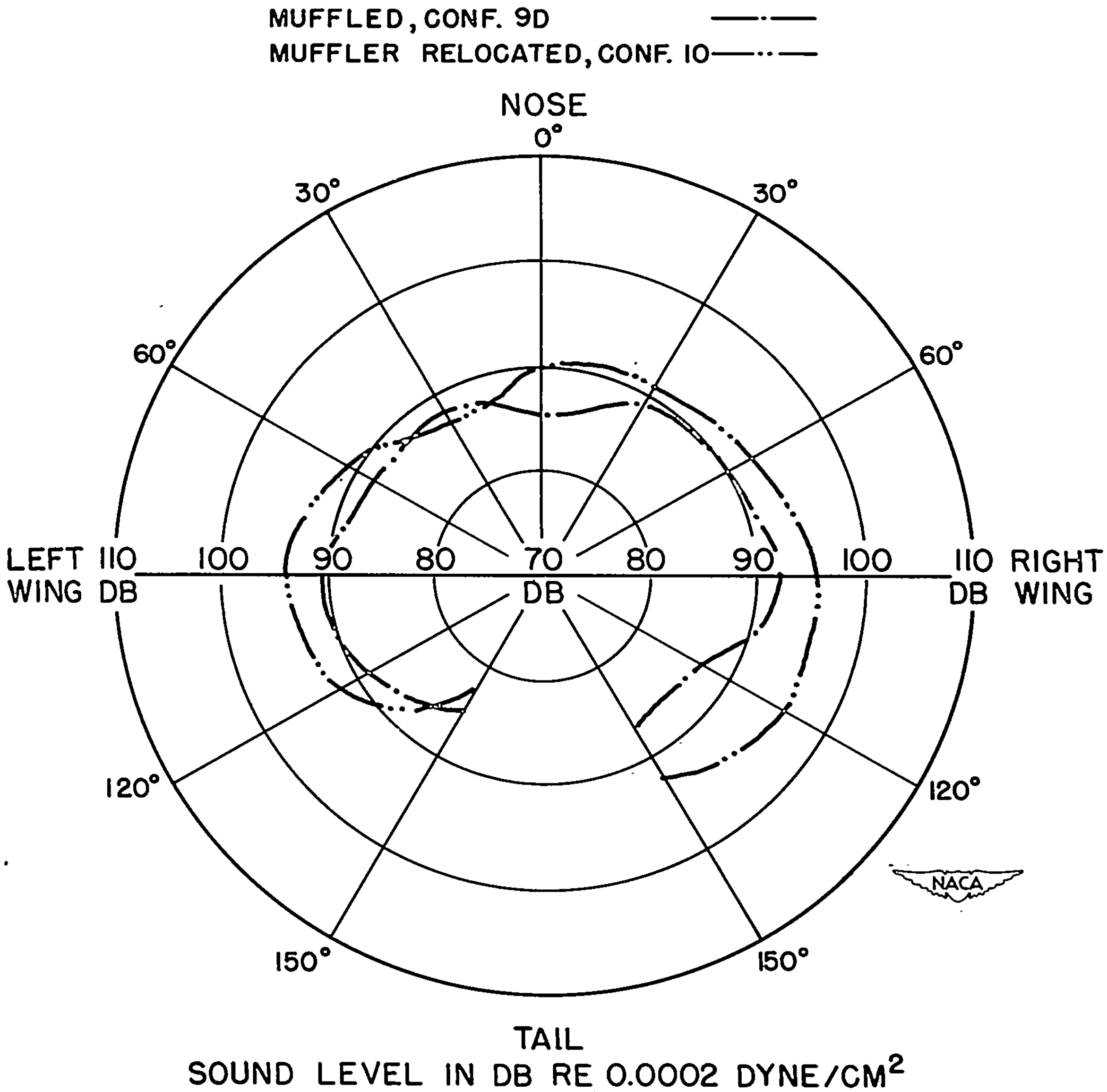
(a) Over-all levels.

Figure 40.- Comparison of over-all levels, engine fundamentals, and propeller fundamentals from frequency analysis on ground 50 feet from hub for configurations of series C. Flat weighting. Refer to table II for engine powers, tip speeds, and propeller diameters. RE indicates "referred to a level of."



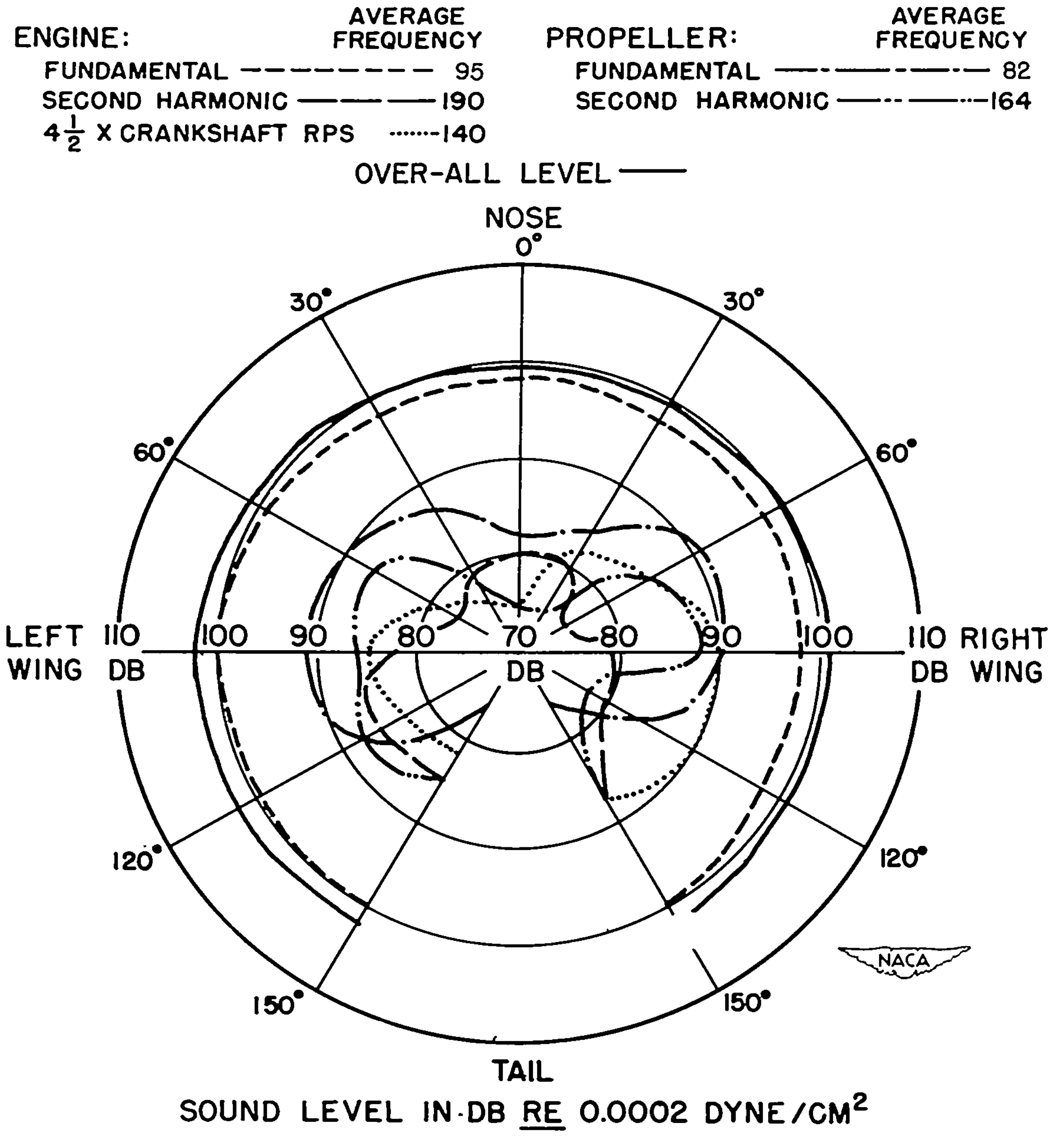
(b) Engine fundamentals.

Figure 40.- Continued.



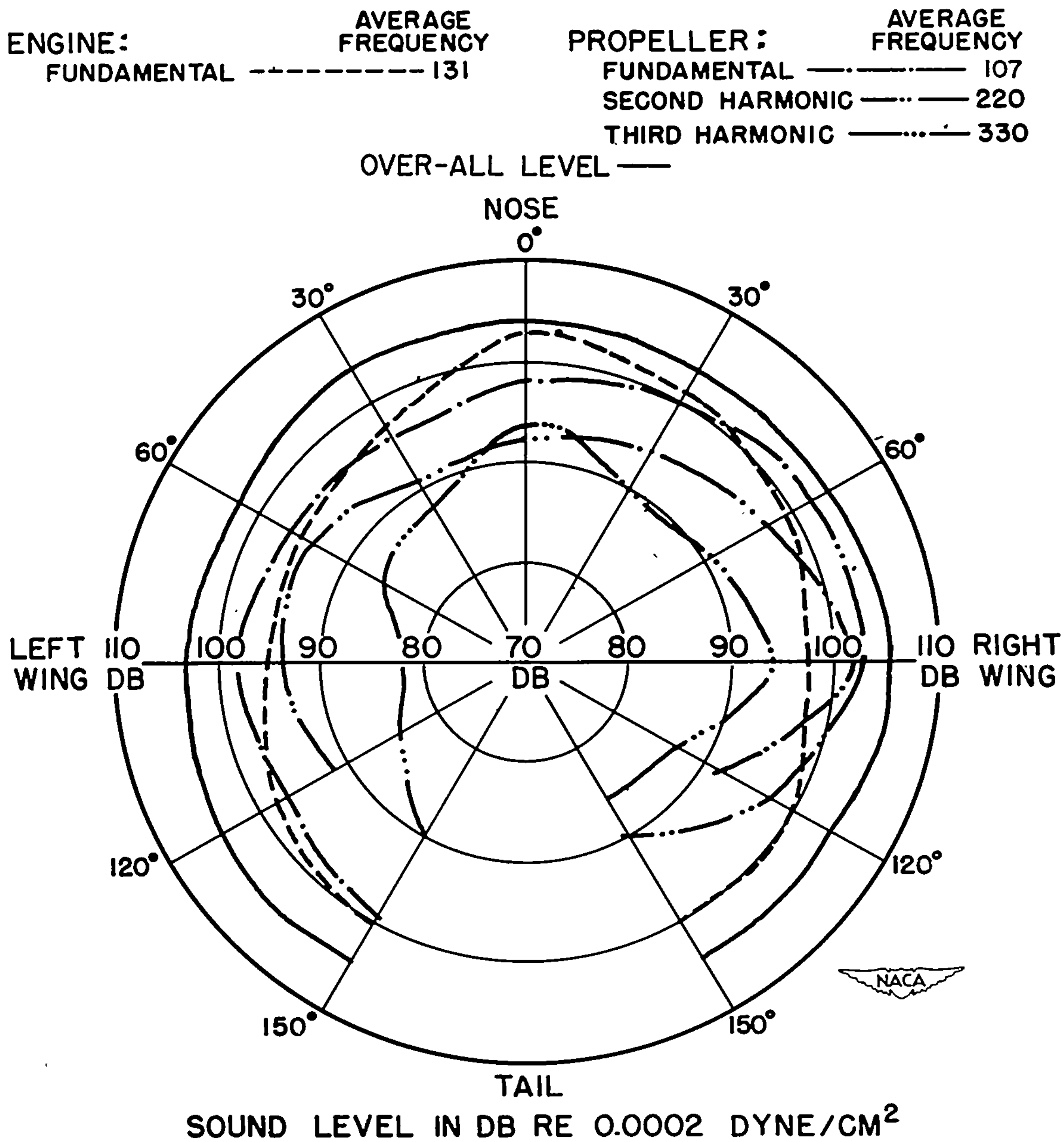
(c) Propeller fundamentals.

Figure 40.- Concluded.



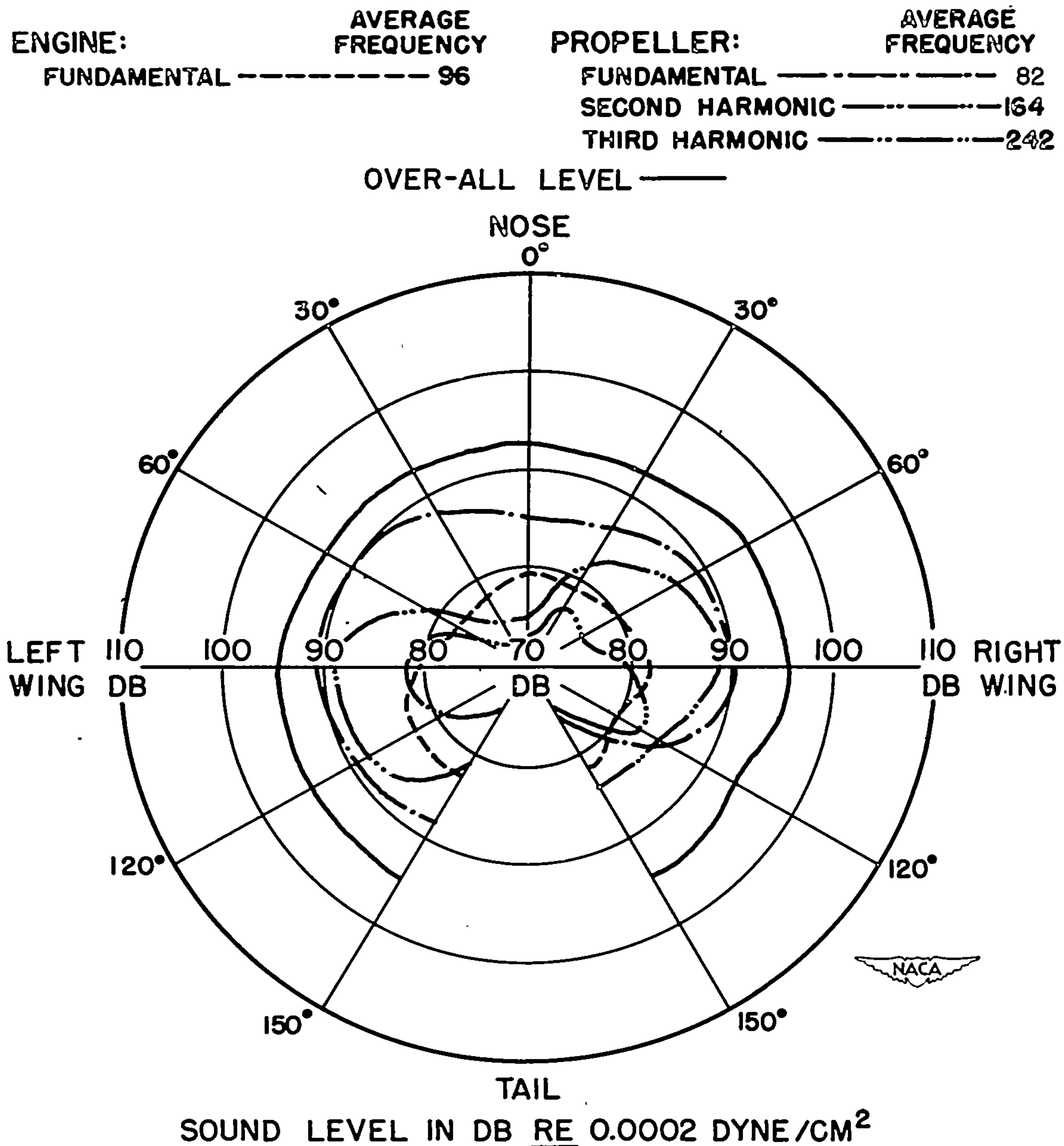
(a) Configuration 8; 1900 rpm.

Figure 41.- Comparison of ground analyses at 1900 and 2500 rpm for configurations of series D. Frequency analysis on ground 50 feet from hub; flat weighting. Refer to table II for engine powers, tip speeds, and propeller diameters. RE indicates "referred to a level of."



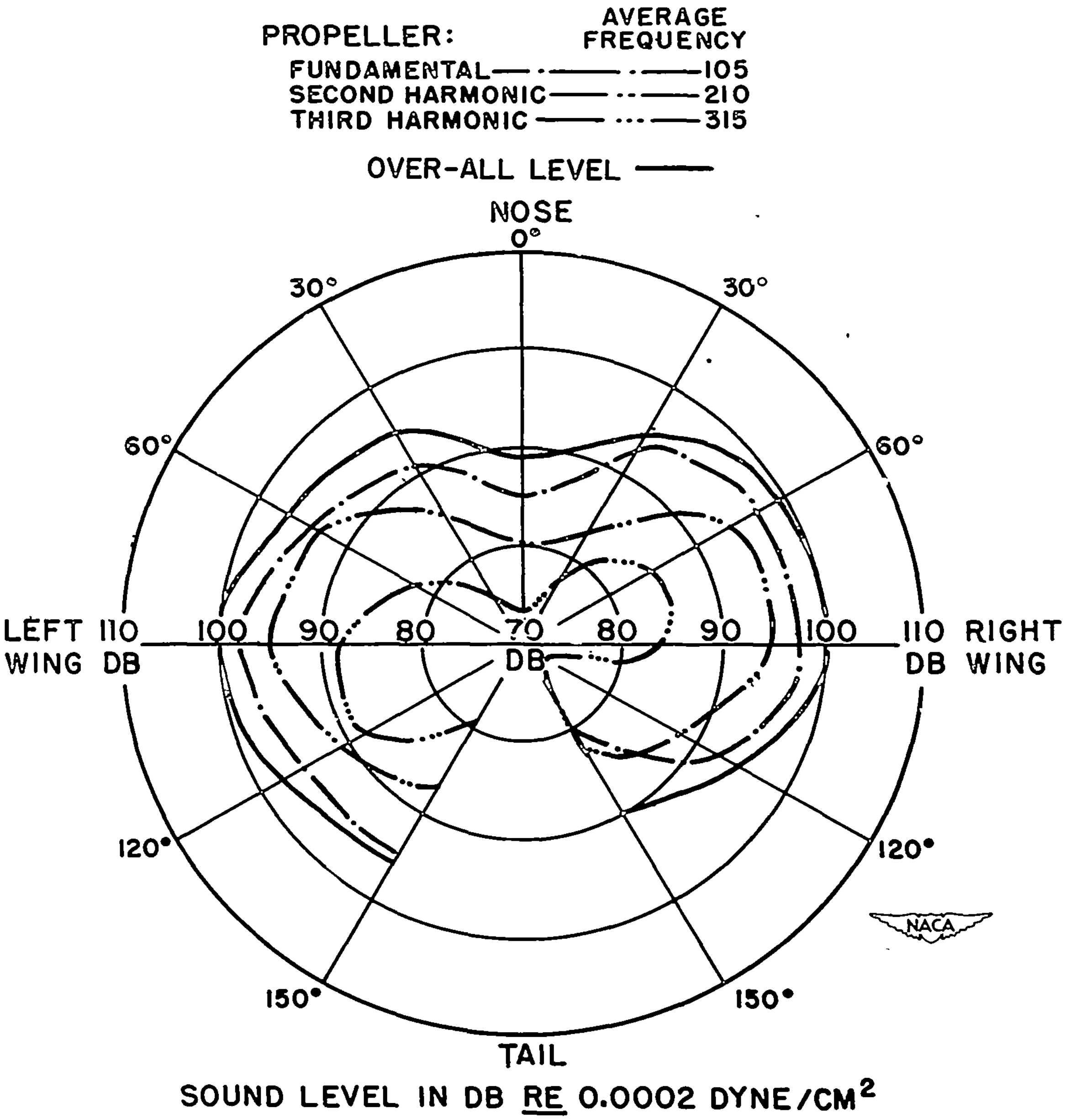
(b) Configuration 8; 2500 rpm.

Figure 41.- Continued.



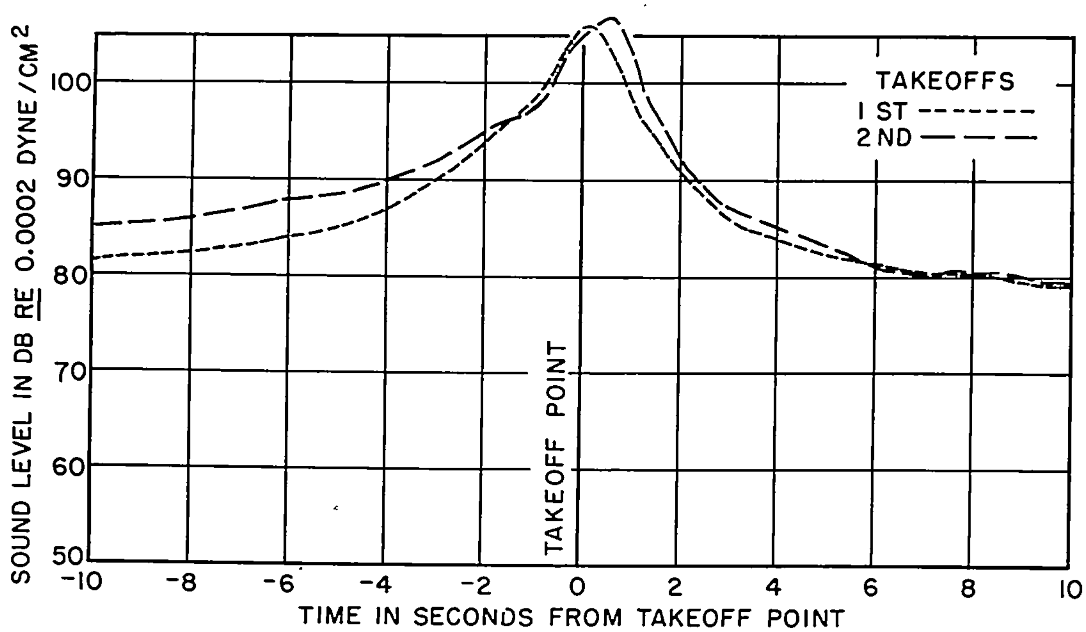
(c) Configuration 9B; 1900 rpm.

Figure 41.- Continued.

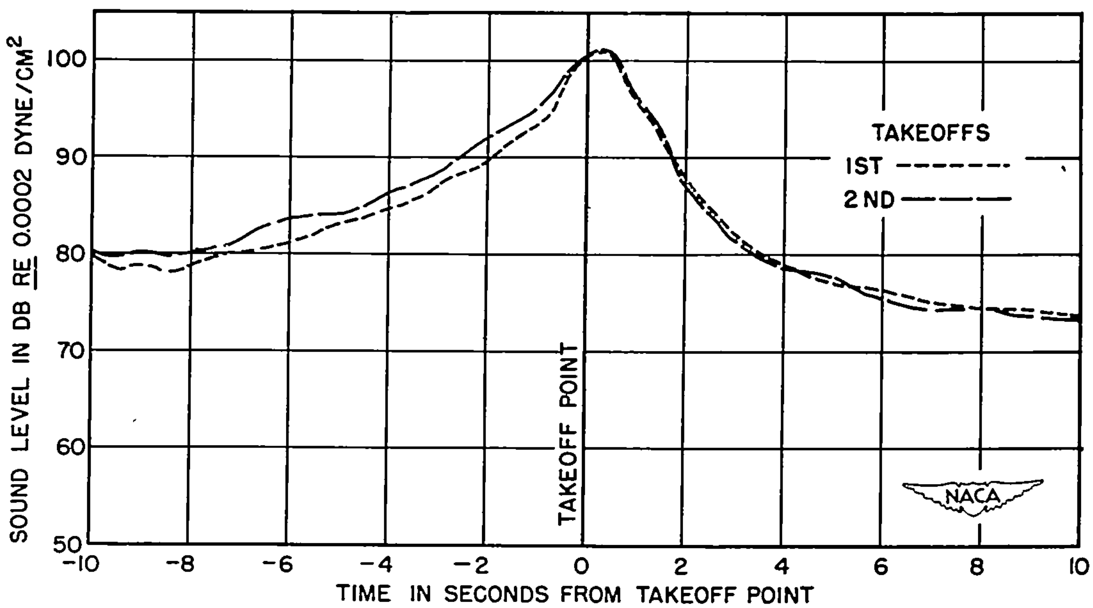


(d) Configuration 9B; 2500 rpm; engine noise masked by propeller.

Figure 41.- Concluded.



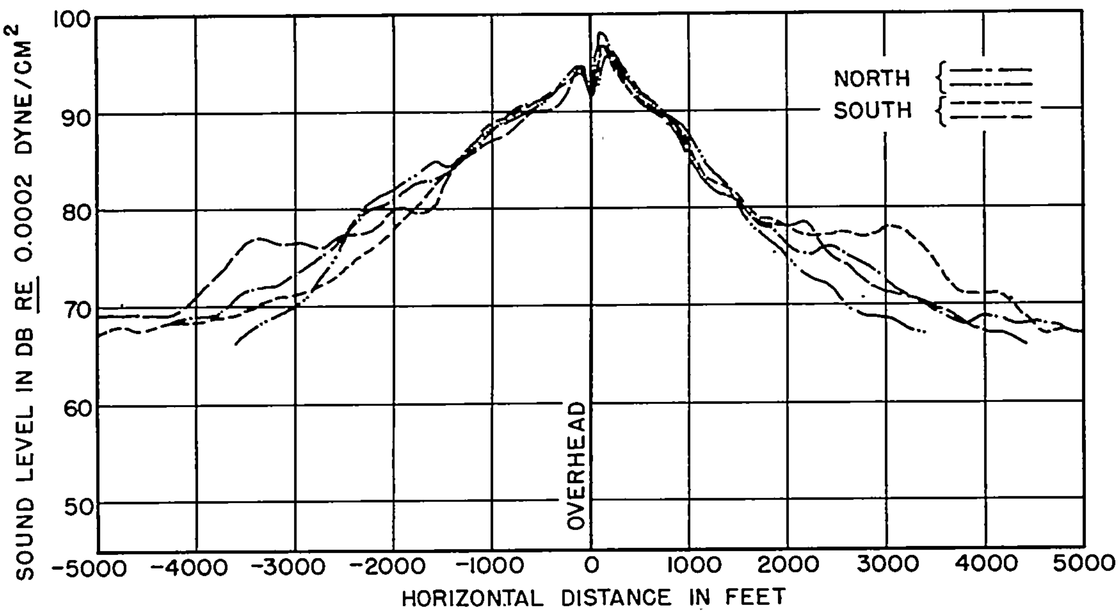
Configuration 6; 2500 to 2600 rpm.



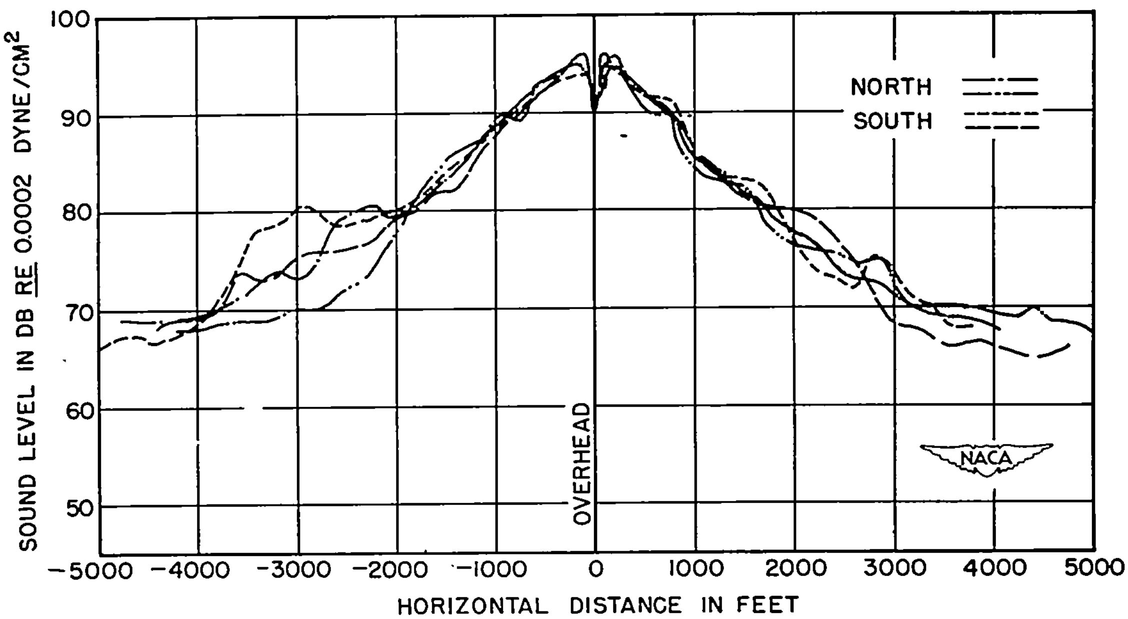
Configuration 7; 2125 rpm.

(a) Take-offs. Flat weighting; airplane leaving ground as it passes 50 feet from microphone.

Figure 42.- Comparison of take-off measurements and of flight measurements at 100-foot altitude for configurations of series E. Refer to table II for engine powers, tip speeds, and propeller diameters. RE indicates "referred to a level of."



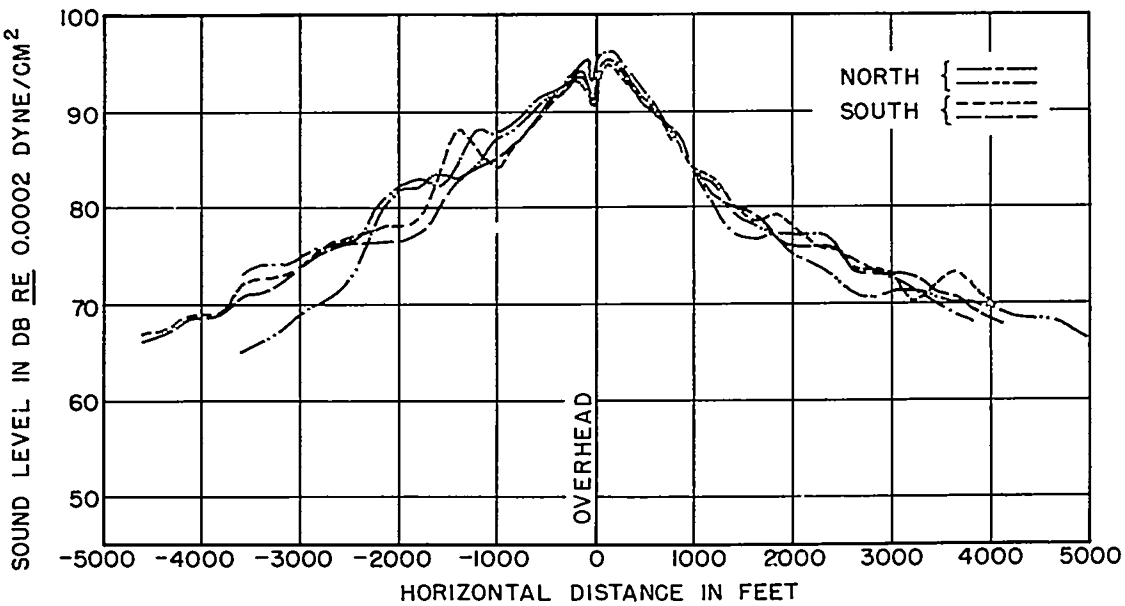
Configuration 6; 2600 rpm; wind - southeast, 1 mph.



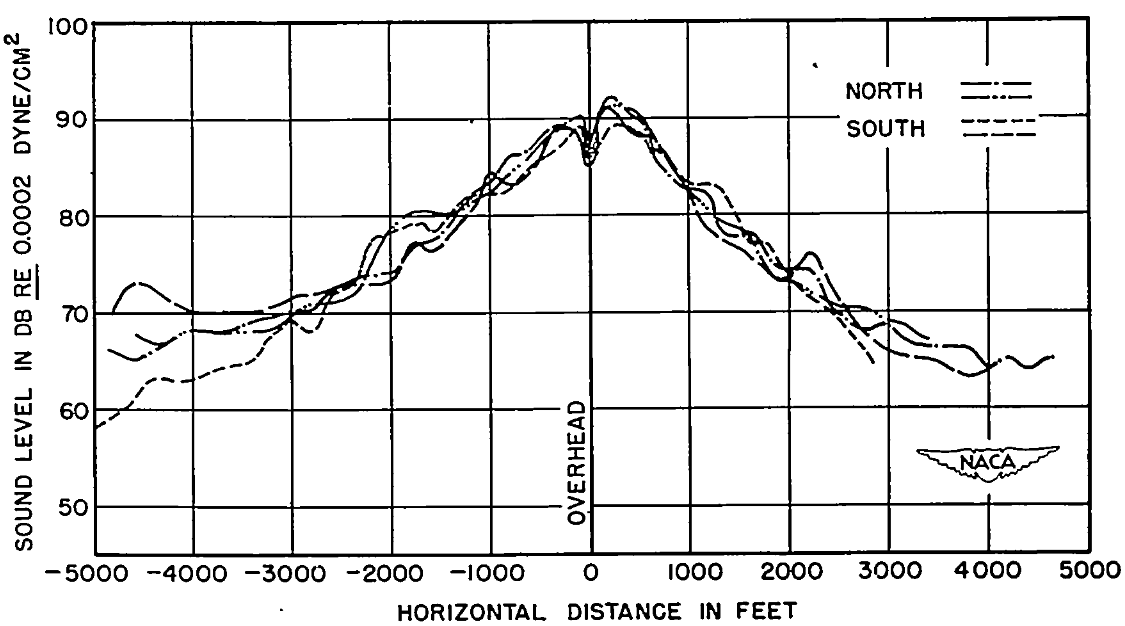
Configuration 7; 2750 rpm; wind - 0 mph.

(b) Flights at 100-foot altitude. Maximum power; flat weighting; airplane passing overhead.

Figure 42.- Continued.



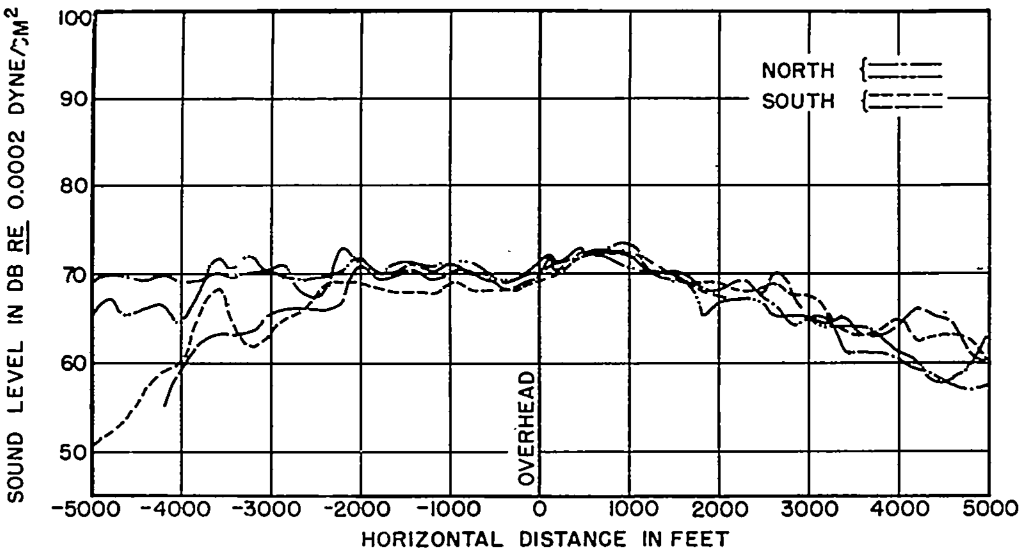
Configuration 6; 2450 rpm; wind - south, 1 mph.



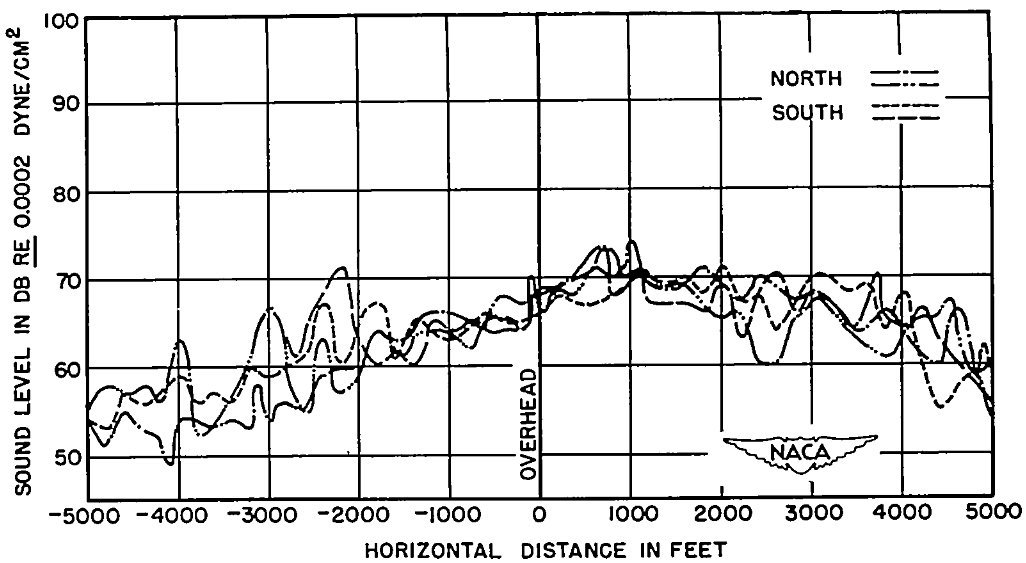
Configuration 7; 2450 rpm; wind - 0 mph.

(c) Flights at 100-foot altitude. Cruising power; flat weighting; airplane passing overhead.

Figure 42.- Concluded.



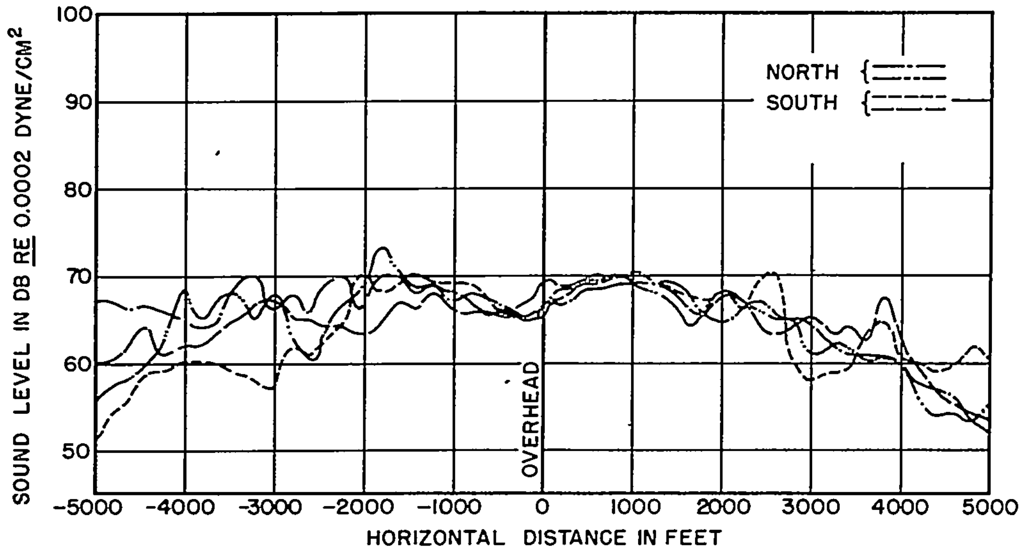
Configuration 6; 2600 rpm; wind - northeast, 2 mph.



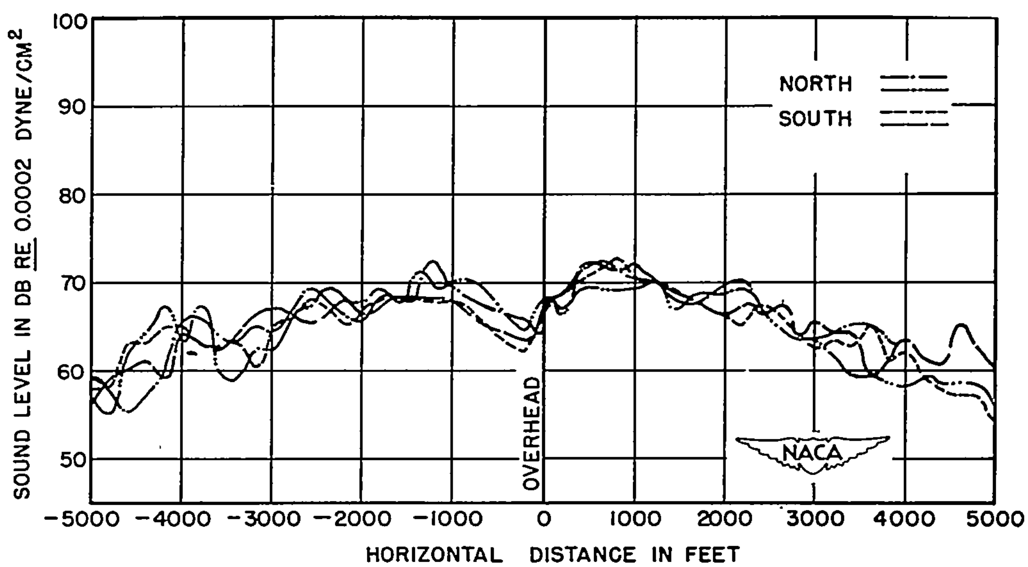
Configuration 7; 2750 rpm; wind - southwest, 5 mph.

(a) Flights at 500-foot altitude. Maximum power; 40-decibel weighting; airplane passing overhead.

Figure 43.- Comparison of flight measurements at 500-foot altitude and of ground analyses for configurations of series E. Refer to table II for engine powers, tip speeds, and propeller diameters. RE indicates "referred to a level of."



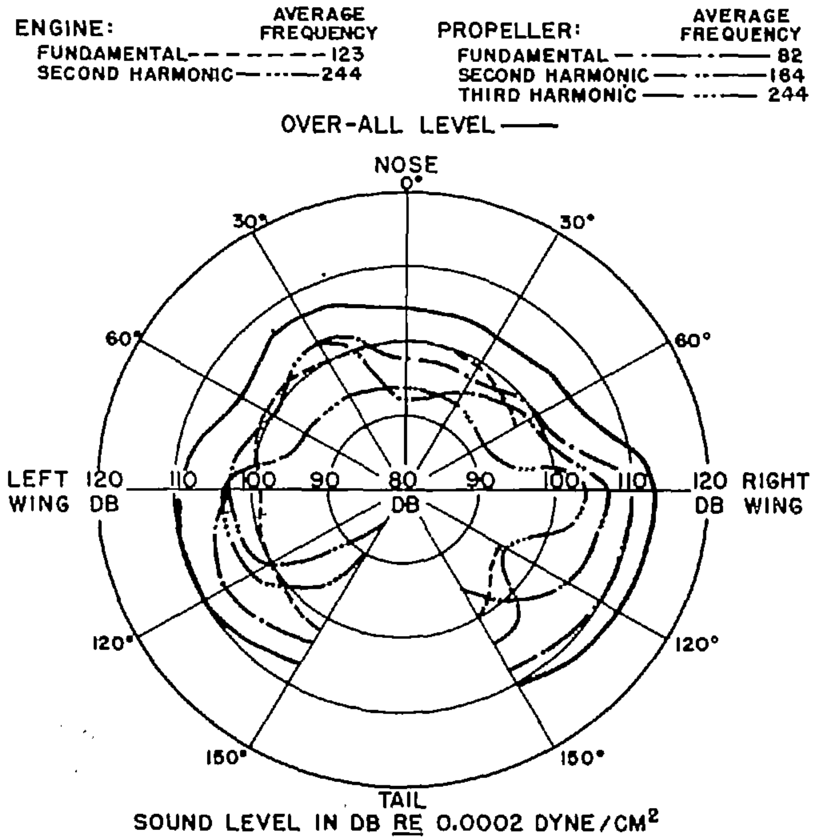
Configuration 6; 2450 rpm; wind - northeast, 2 mph.



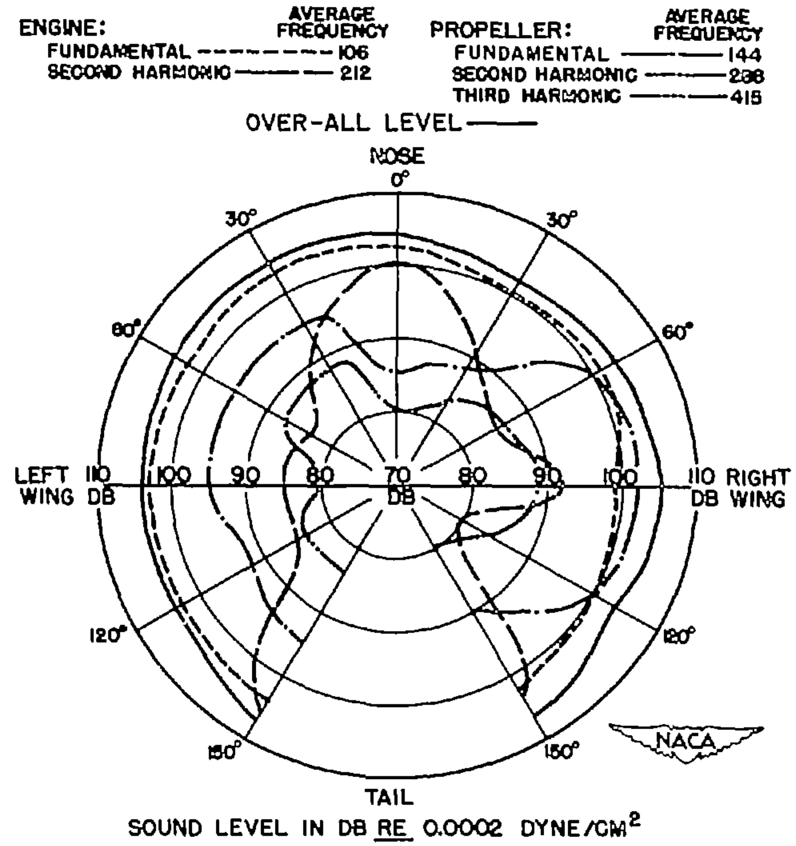
Configuration 7; 2450 rpm; wind - west, 5 mph.

(b) Flights at 500-foot altitude. Cruising power; 40-decibel weighting; airplane passing overhead.

Figure 43.- Continued.



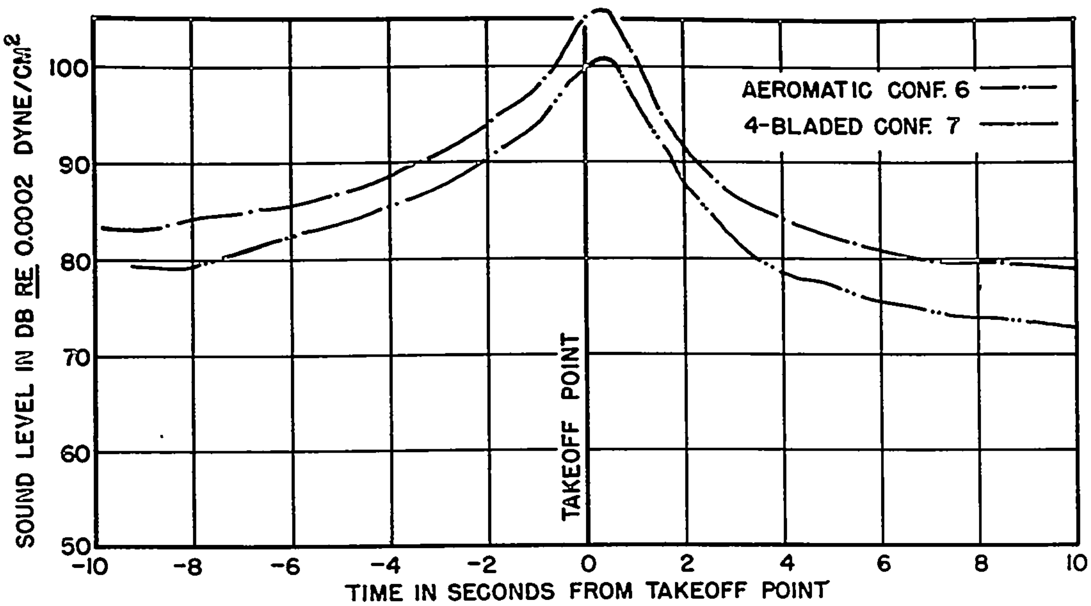
Configuration 6; 2500 rpm; engine second harmonic and propeller third harmonic occur at same frequency; engine fundamental not measurable at 90° right position.



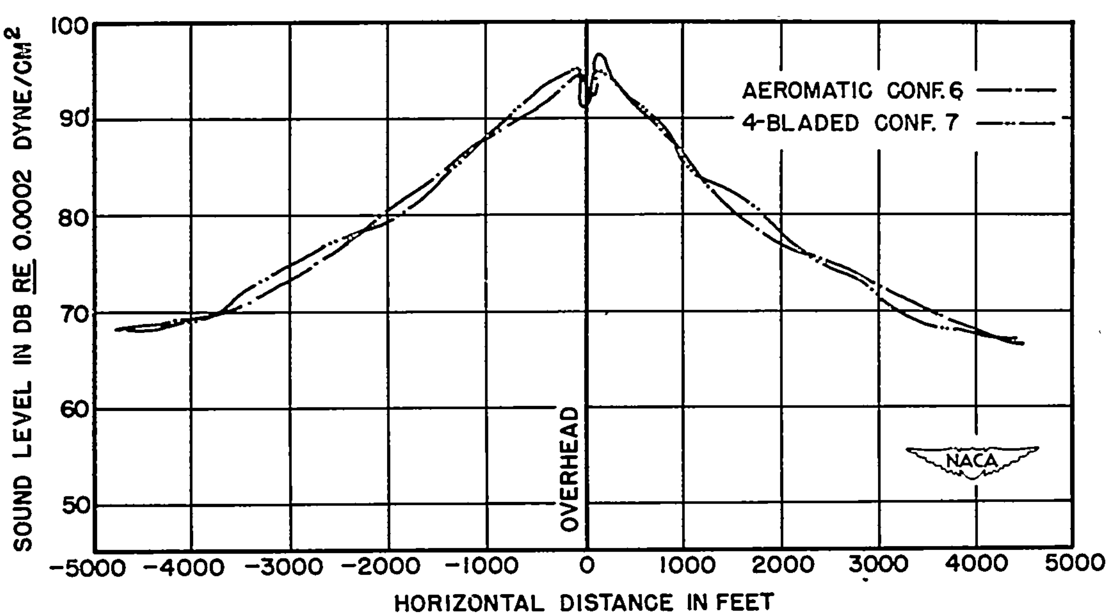
Configuration 7; 2125 rpm.

(c) Frequency analysis on ground 50 feet from hub. Flat weighting.

Figure 43.- Concluded.

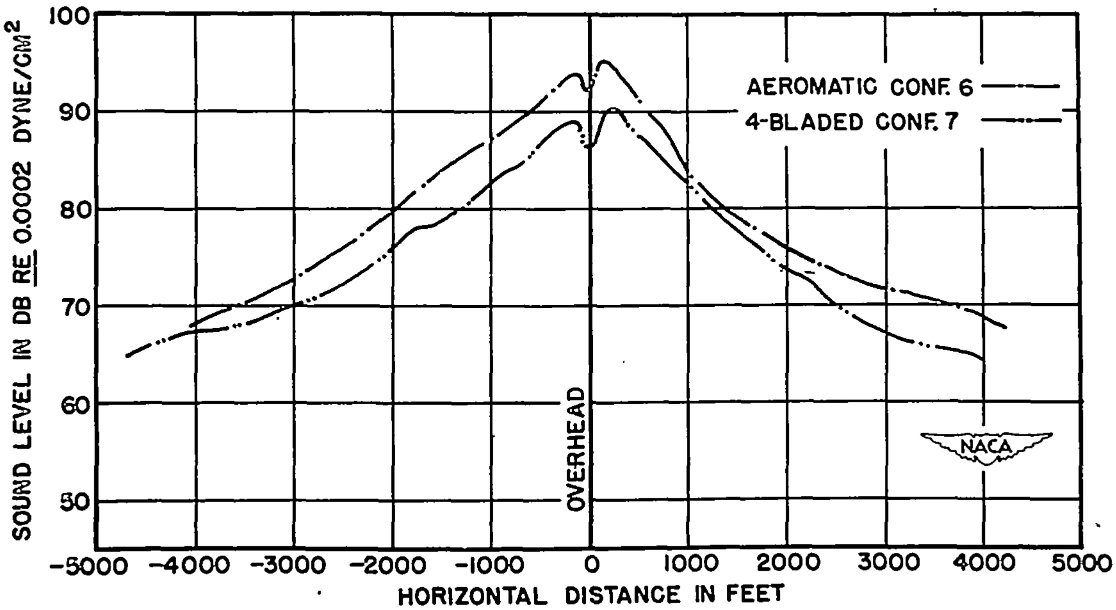


(a) Averages of take-offs. Flat weighting; airplane leaving ground as it passes 50 feet from microphone.



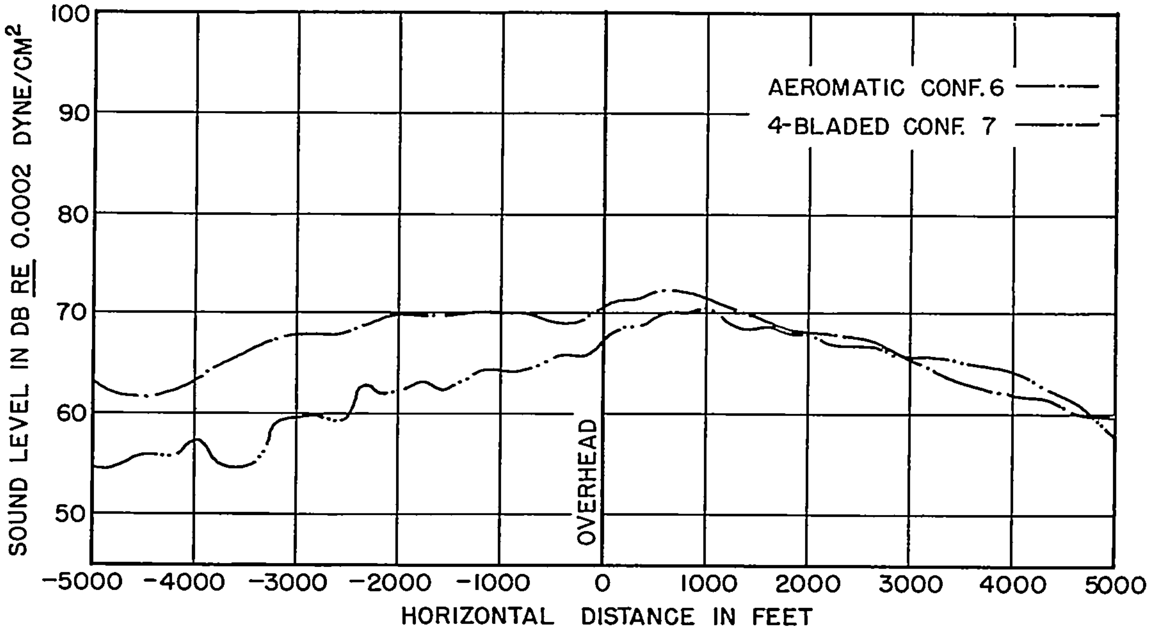
(b) Averages of flights at 100-foot altitude. Maximum power; flat weighting; airplane passing overhead.

Figure 44.- Average curves of take-offs and of flights at 100-foot altitude for configurations of series E. Refer to table II for engine powers, tip speeds, and propeller diameters. RE indicates "referred to a level of."

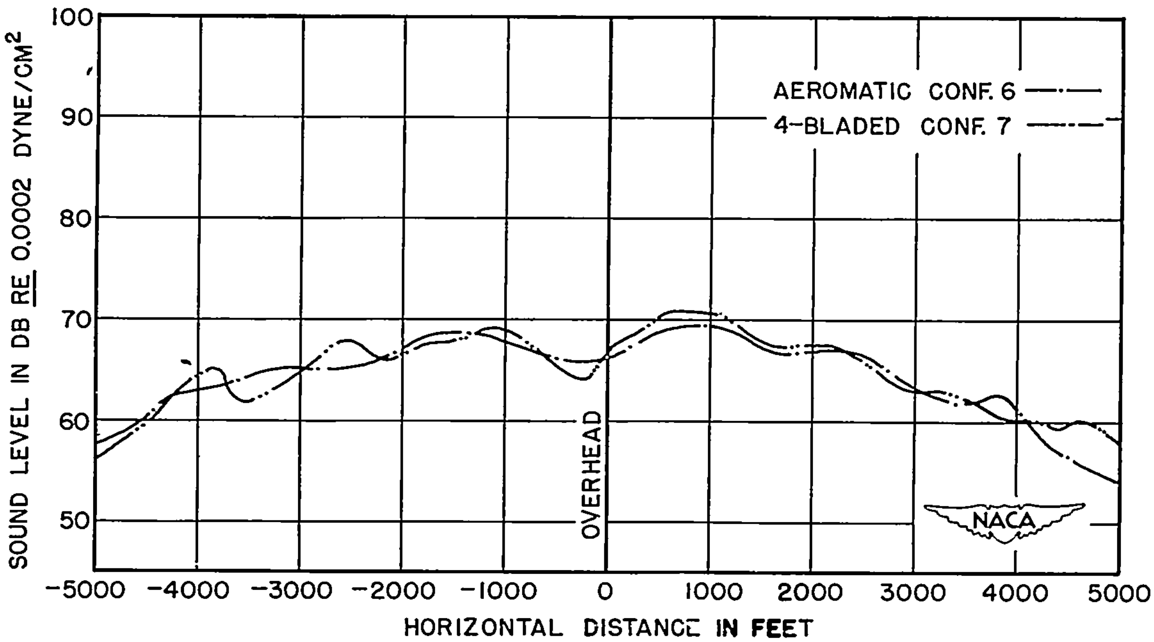


(c) Averages of flights at 100-foot altitude. Cruising power; flat weighting; airplane passing overhead.

Figure 44.- Concluded.

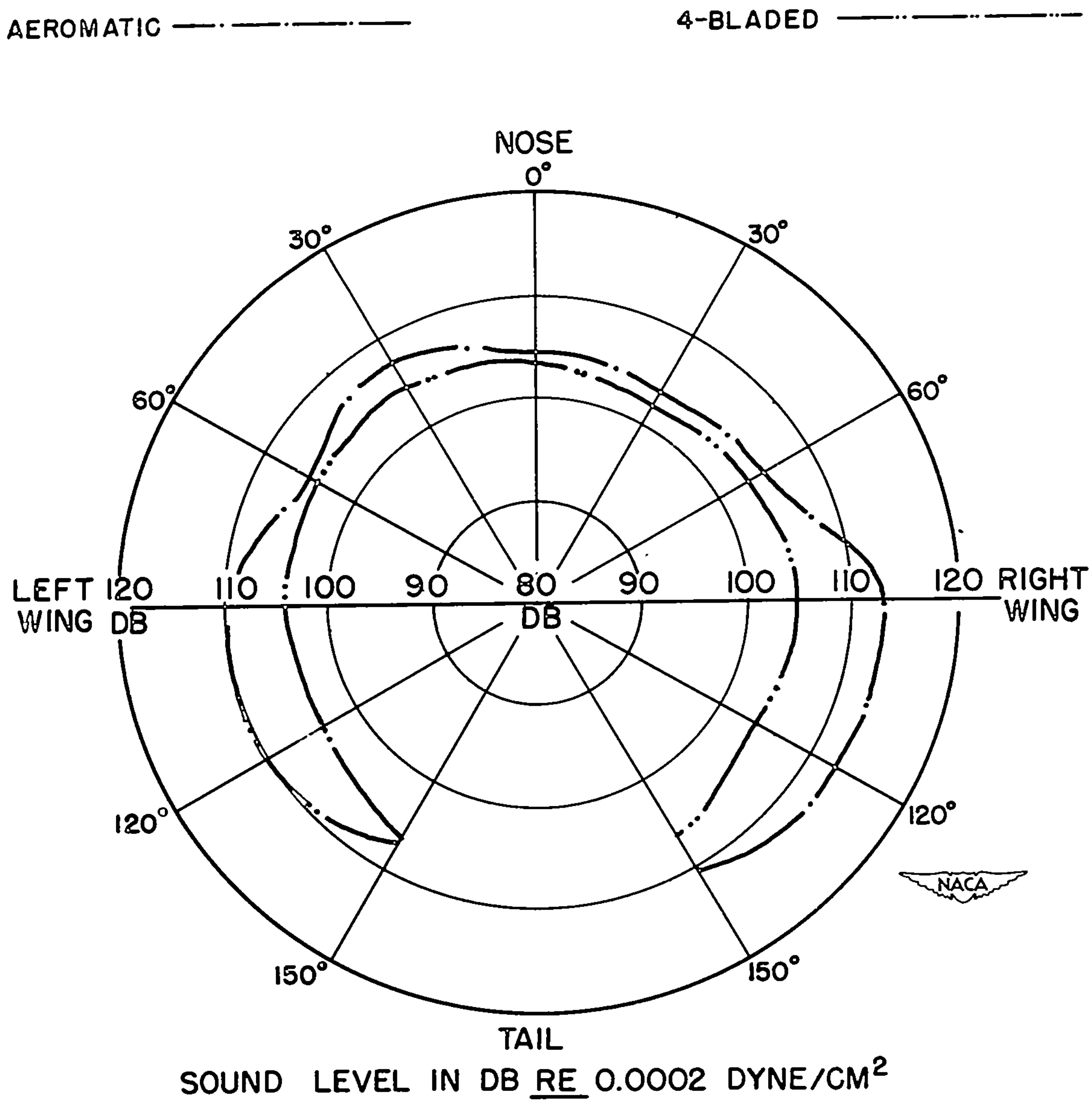


(a) Maximum power.



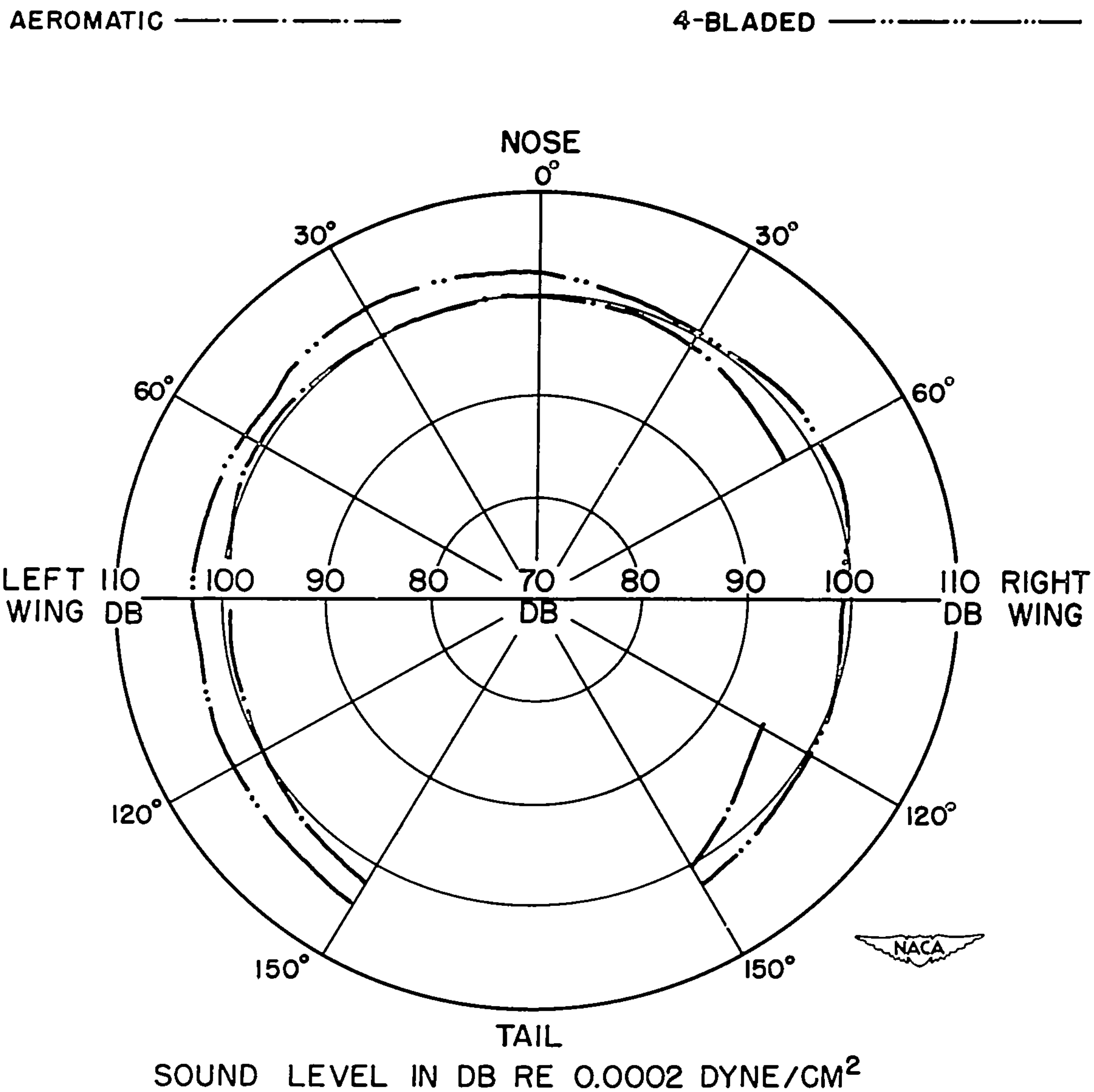
(b) Cruising power.

Figure 45.- Average curves of flights at 500-foot altitude for configurations of series E. 40-decibel weighting; airplane passing overhead. Refer to table II for engine powers, tip speeds, and propeller diameters. RE indicates "referred to a level of."



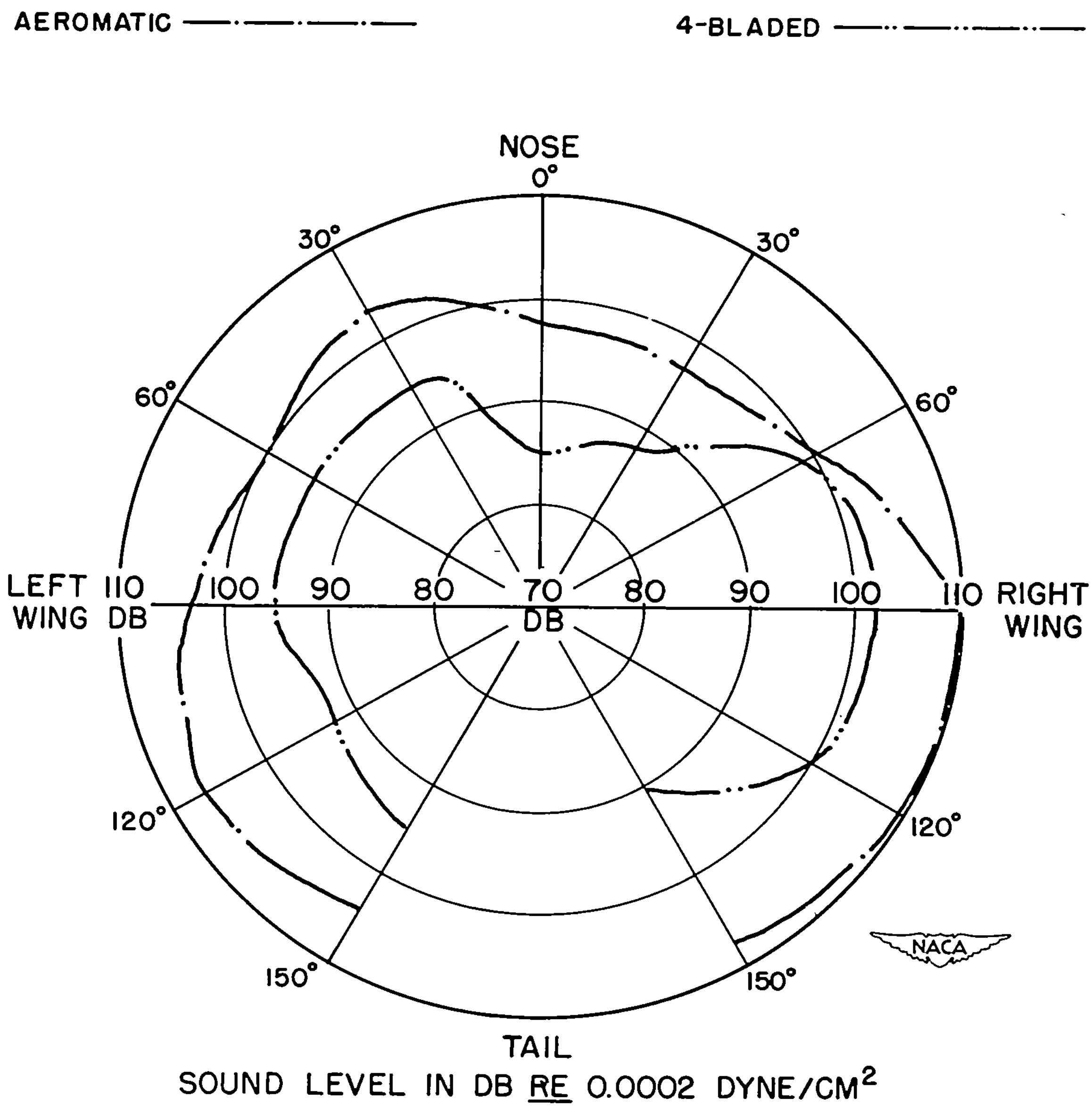
(a) Over-all levels.

Figure 46.- Comparison of over-all levels, engine fundamentals, and propeller fundamentals from frequency analysis on ground 50 feet from hub for configurations of series E. Flat weighting. Refer to table II for engine powers, tip speeds, and propeller diameters. RE indicates "referred to a level of."



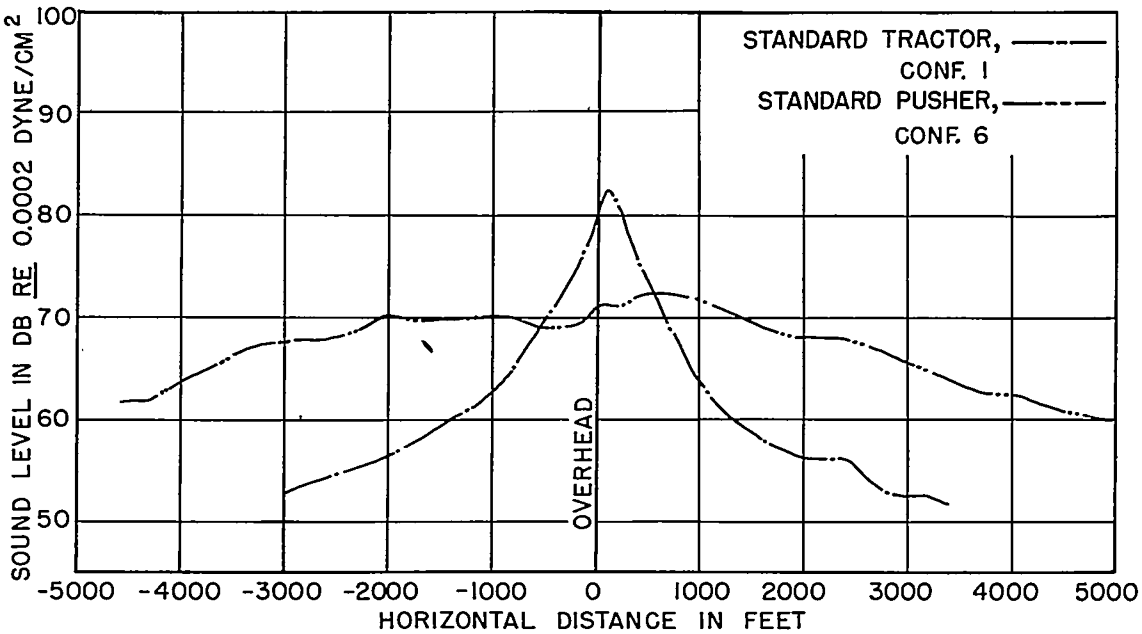
(b) Engine fundamentals.

Figure 46.- Continued.

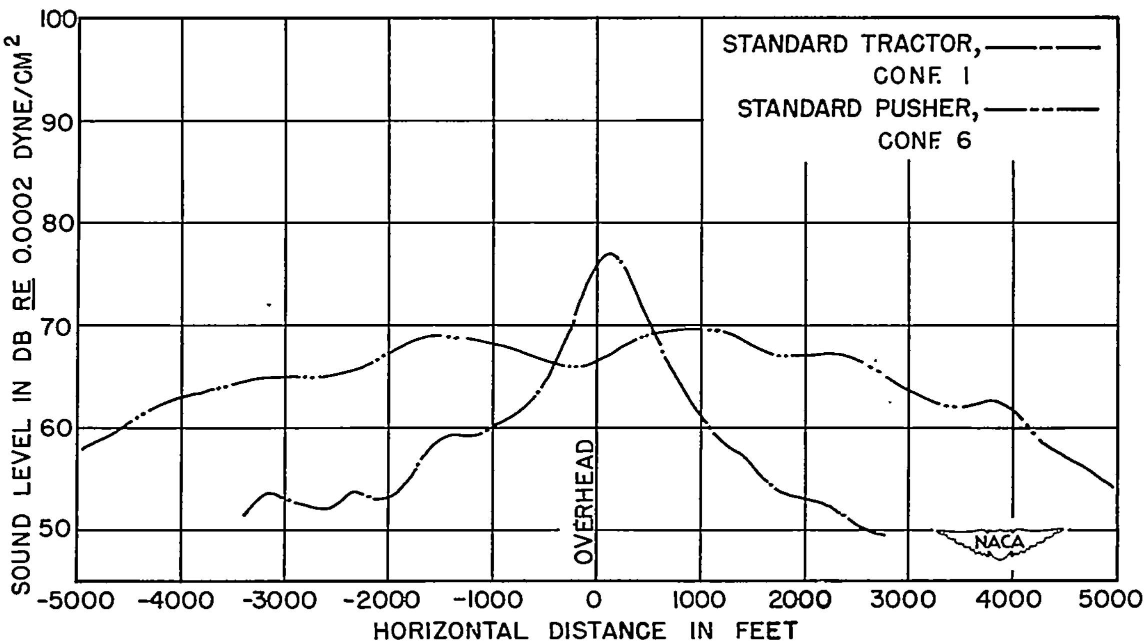


(c) Propeller fundamentals.

Figure 46.- Concluded.

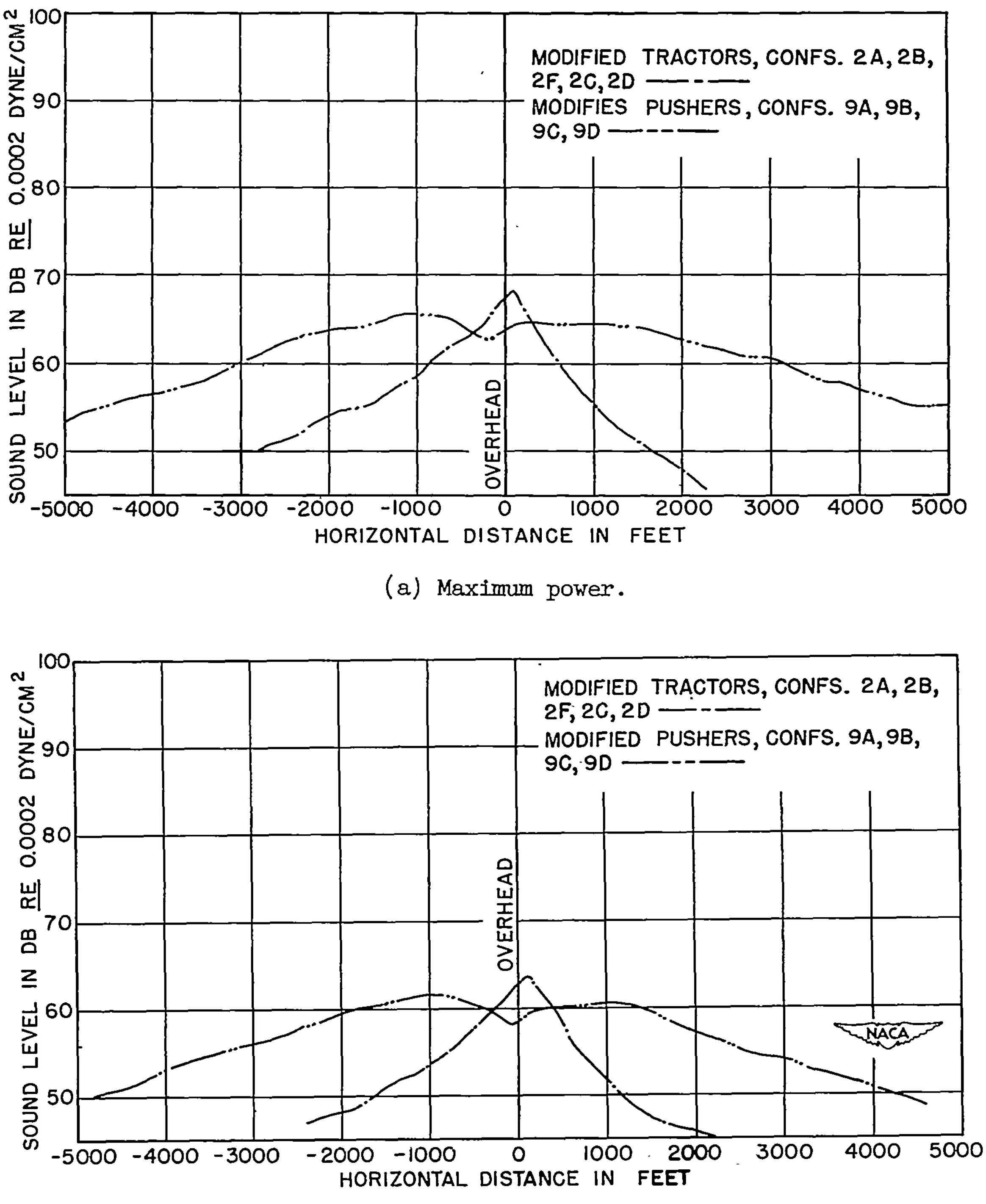


(a) Maximum power.



(b) Cruising power.

Figure 47.- Average curves of flights at 500-foot altitude for standard configurations of series F. 40-decibel weighting; airplane passing overhead. Refer to table II for engine powers, tip speeds, and propeller diameters. RE indicates "referred to a level of."



(a) Maximum power.

(b) Cruising power.

Figure 48.- Average curves of flights at 500-foot altitude for modified configurations of series F. 40-decibel weighting; airplane passing overhead. Refer to table II for engine powers, tip speeds, and propeller diameters. RE indicates "referred to a level of."

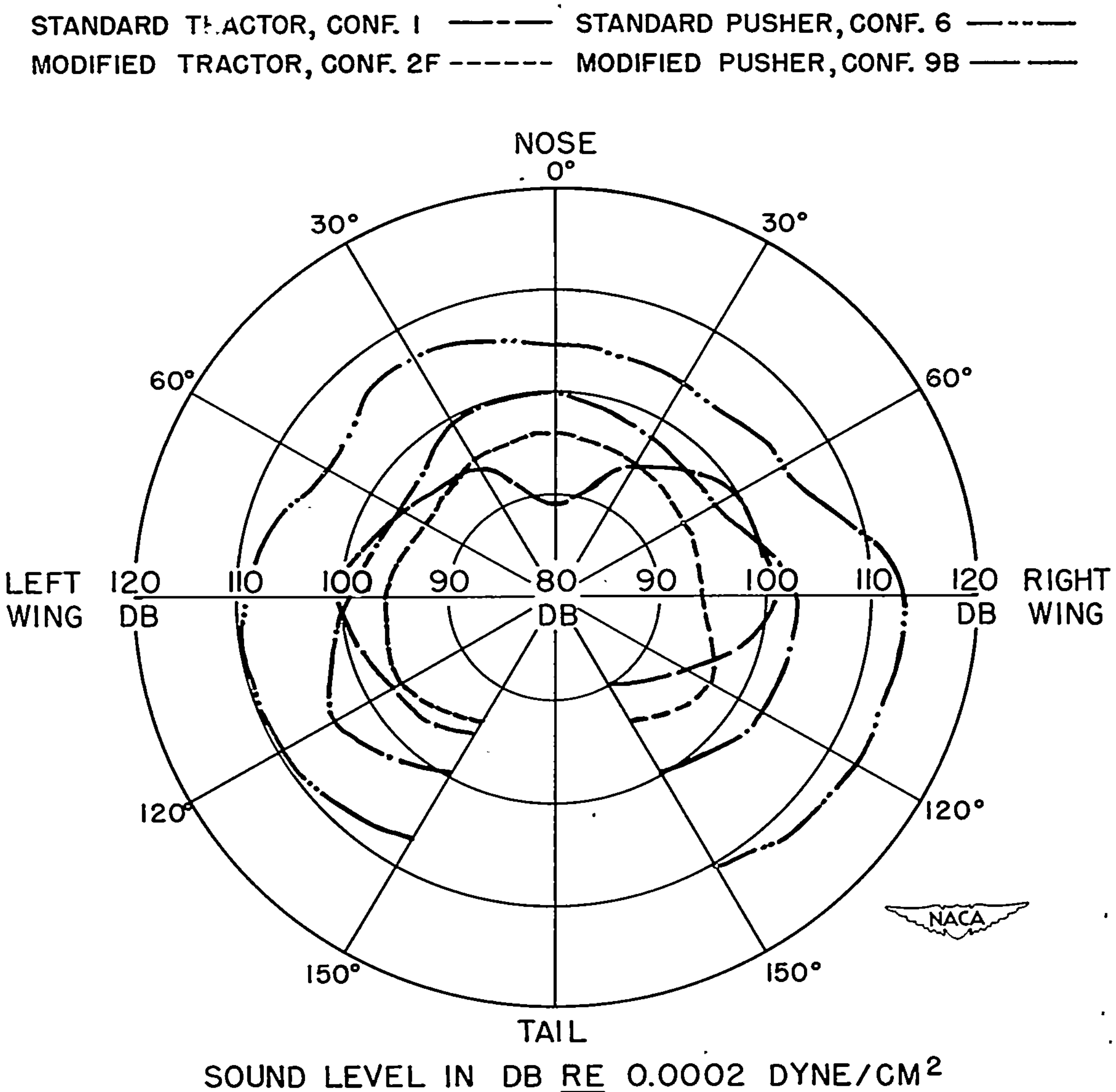
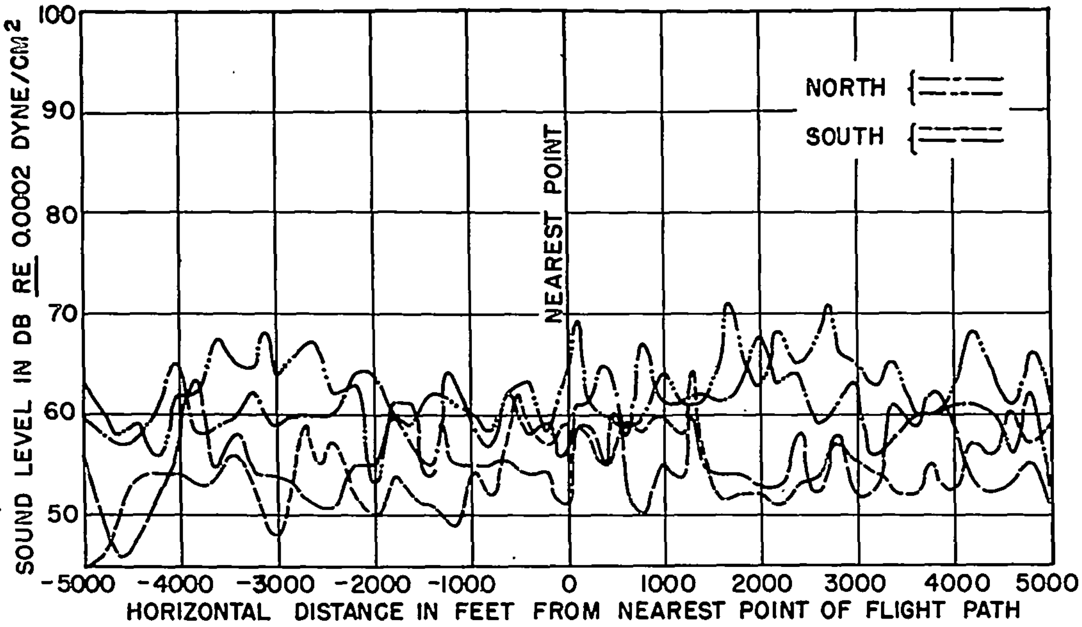
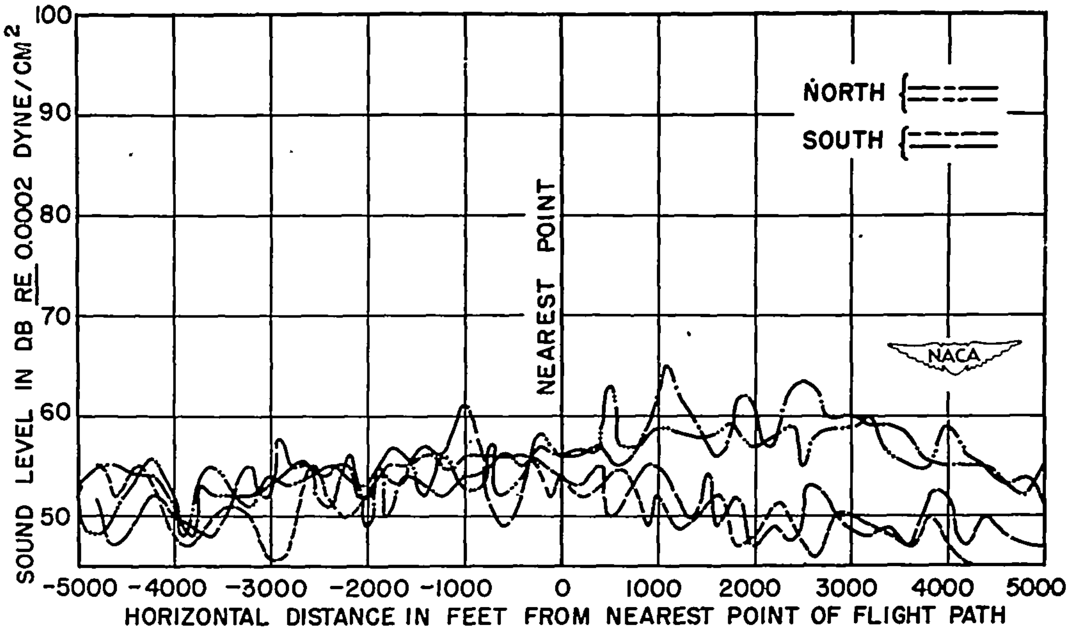


Figure 49.- Comparison of over-all levels from frequency analysis on ground 50 feet from hub for standard and modified configurations of series F. Flat weighting. Refer to table II for engine powers, tip speeds, and propeller diameters. RE indicates "referred to a level of."

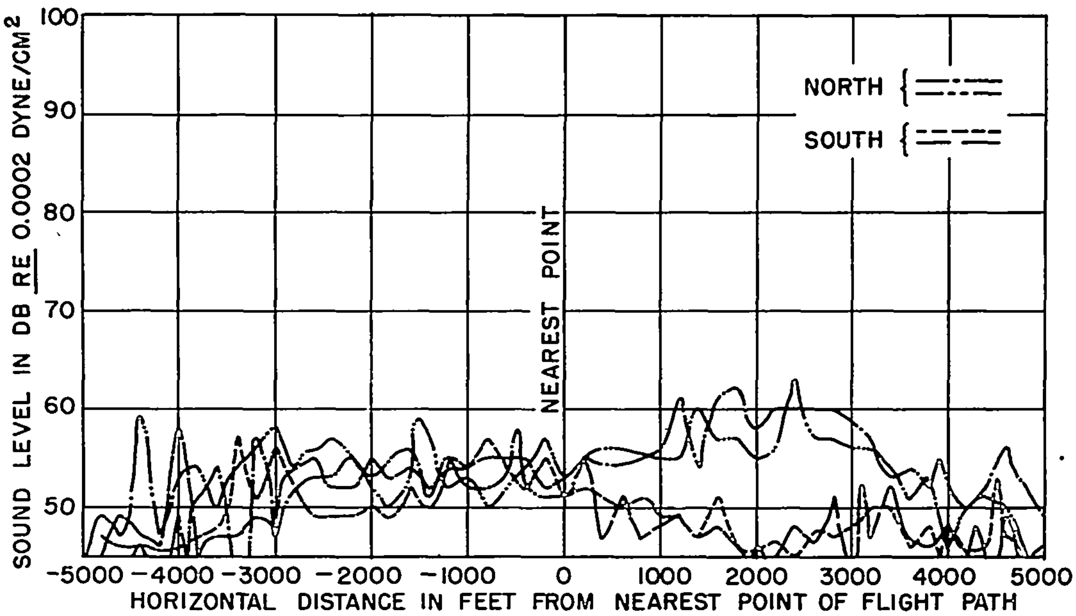


(a) Configuration 6 - standard pusher, Aeromatic propeller. 2600 rpm; wind - west, 3 mph.

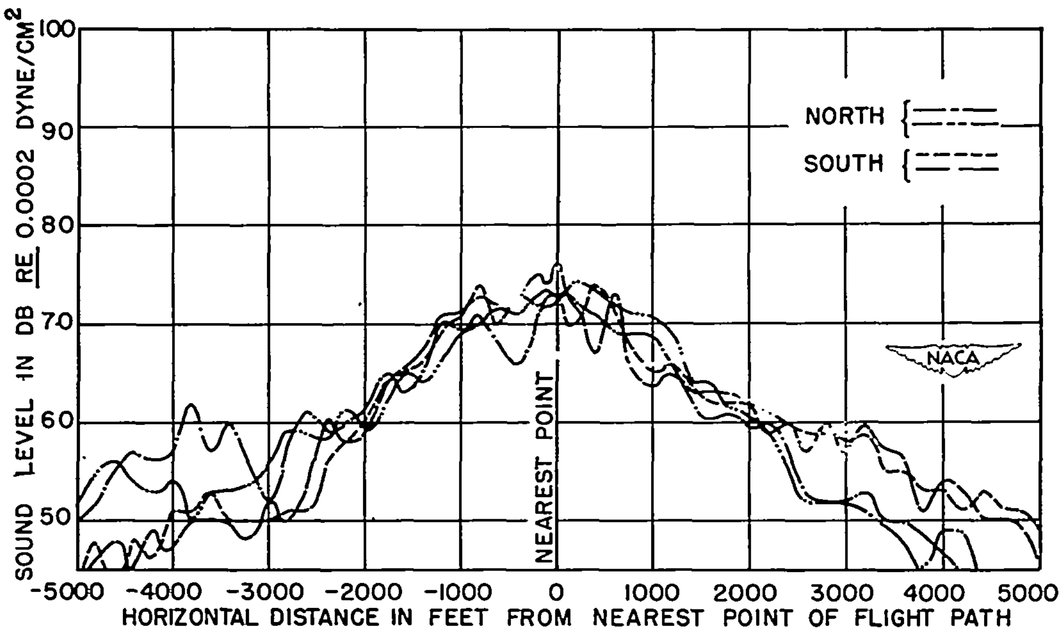


(b) Configuration 8 - modified pusher, unmuffled, four-bladed propeller. 2500 rpm; wind - west, 2 mph.

Figure 50.- Measurements of flights passing 3000 feet away for configurations of series G. 500-foot altitude; maximum power; 40-decibel weighting. Refer to table II for engine powers, tip speeds, and propeller diameters. RE indicates "referred to a level of."

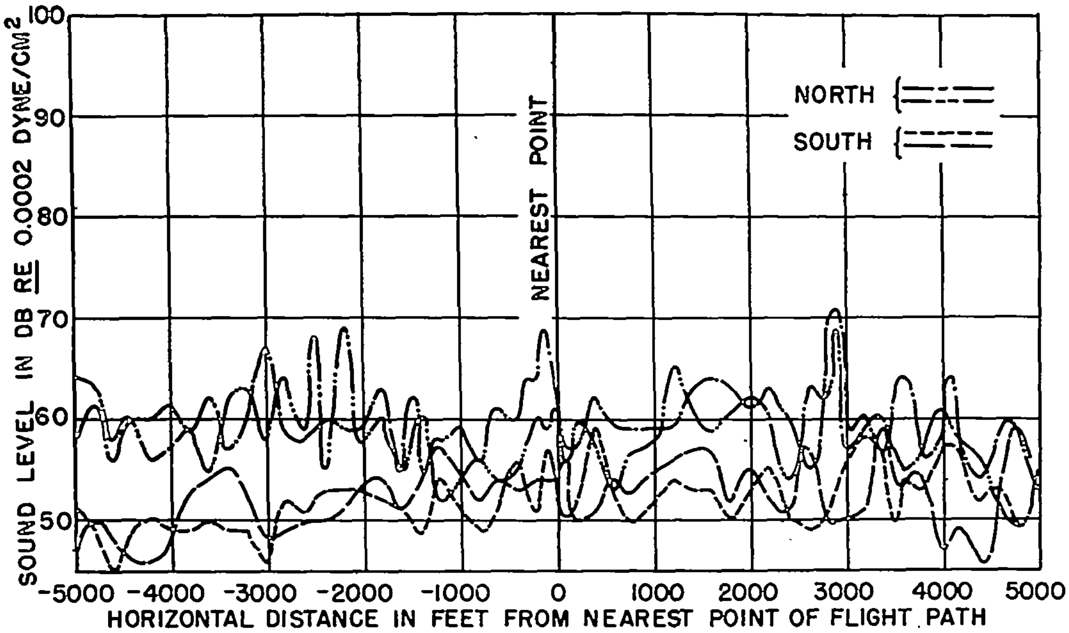


(c) Configuration 9B - modified pusher, muffled, four-bladed propeller. 2500 rpm; wind - 0 mph.

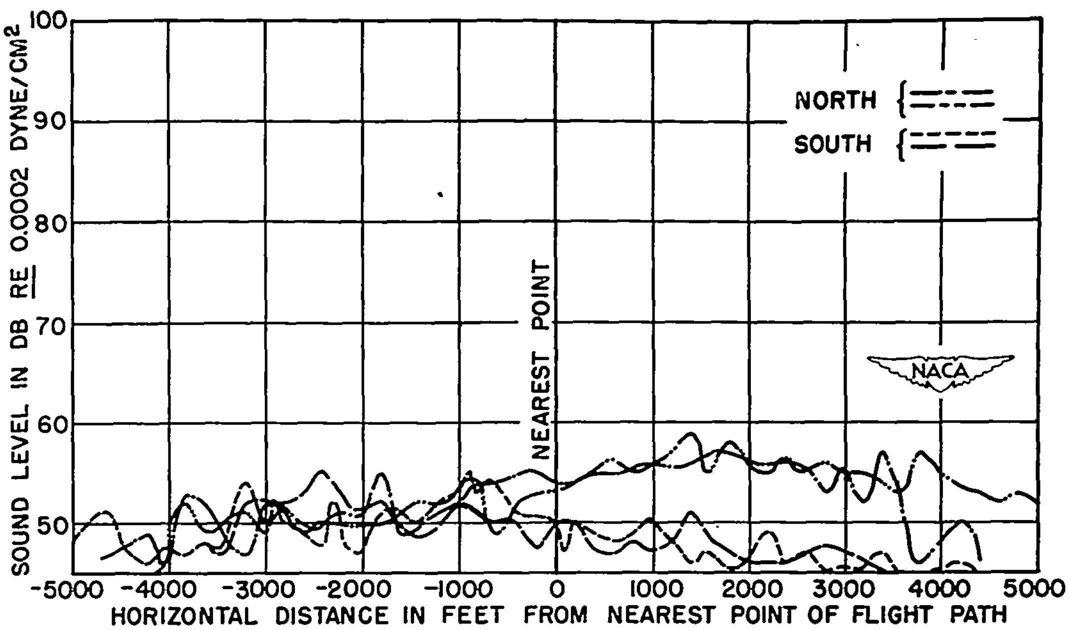


(d) Configuration 5 - standard tractor, two-bladed propeller. 2800 rpm.

Figure 50.- Concluded.

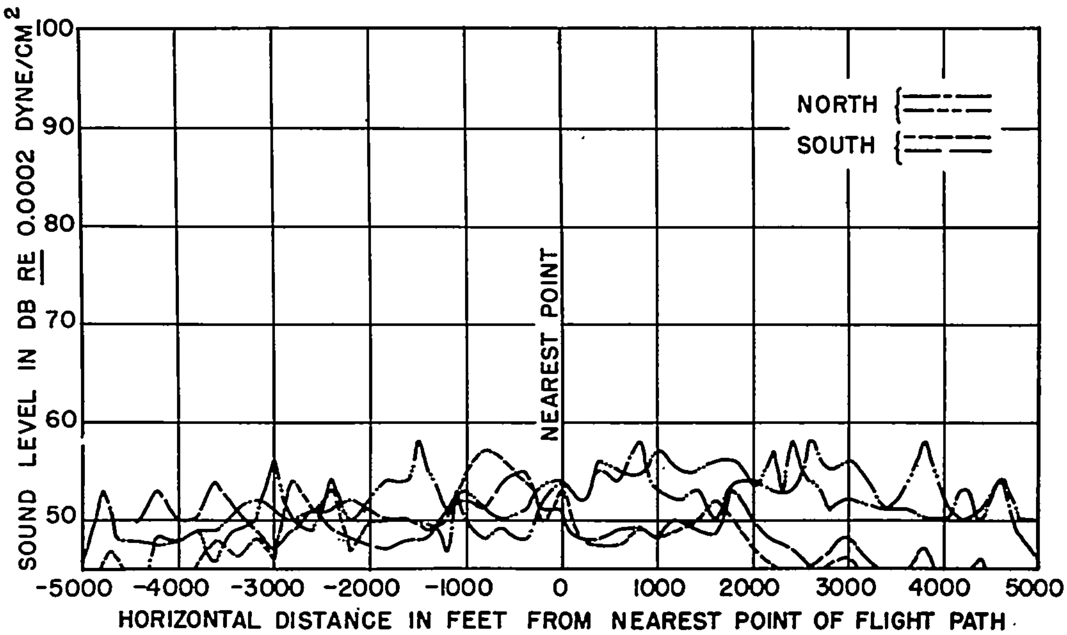


(a) Configuration 6 - standard pusher, Aeromatic propeller. 2450 rpm; wind - west, 3 mph.

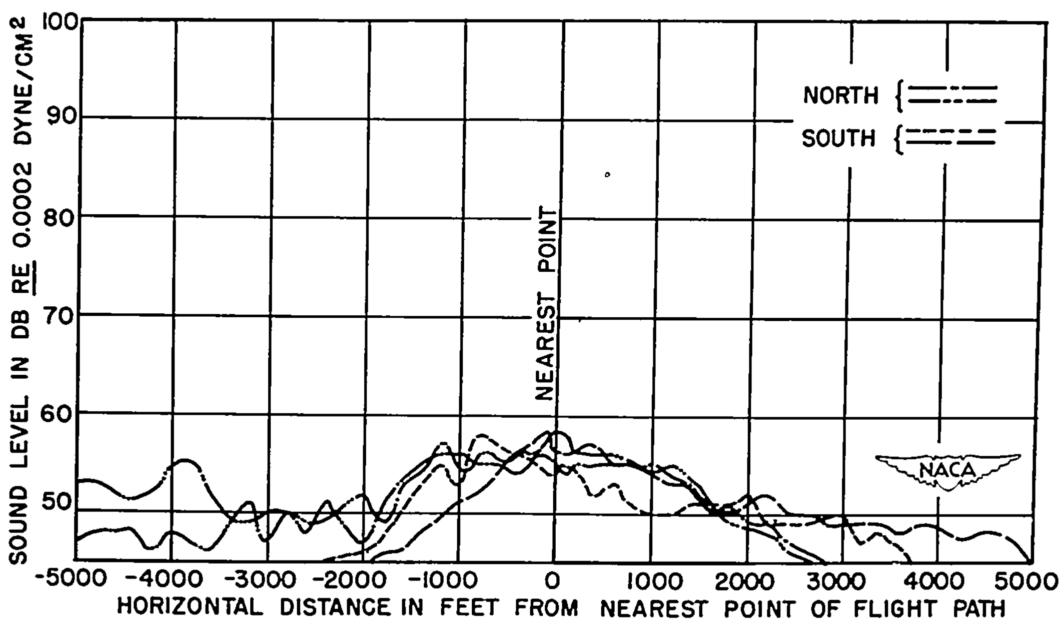


(b) Configuration 8 - modified pusher, unmuffled, four-bladed propeller. 2250 rpm; wind - west, 2 mph.

Figure 51.- Measurements of flights passing 3000 feet away for configurations of series G. 500-foot altitude; cruising power; 40-decibel weighting. Refer to table II for engine powers, tip speeds, and propeller diameters. RE indicates "referred to a level of."

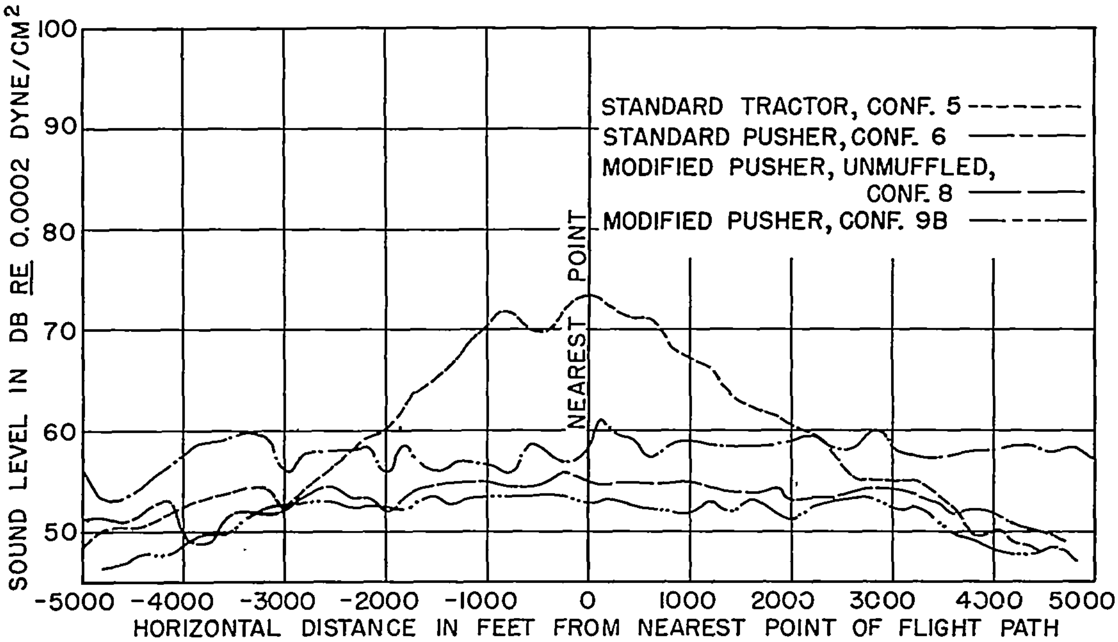


(c) Configuration 9B - modified pusher, muffled, four-bladed propeller. 2250 rpm; wind - 0 mph.

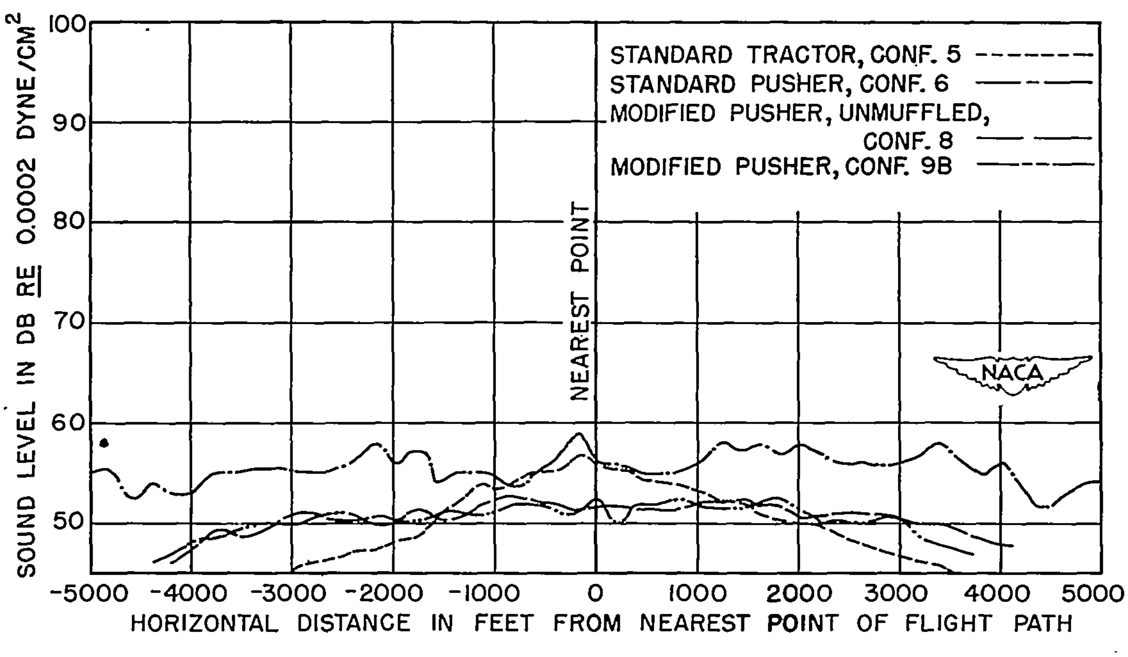


(d) Configuration 5 - standard tractor, two-bladed propeller. 2450 rpm; wind - 0 mph.

Figure 51.- Concluded.



(a) Maximum power.



(b) Cruising power.

Figure 52.- Average curves of flights passing 3000 feet away for configurations of series G. 500-foot altitude; 40-decibel weighting. Refer to table II for engine powers, tip speeds, and propeller diameters. RE indicates "referred to a level of."

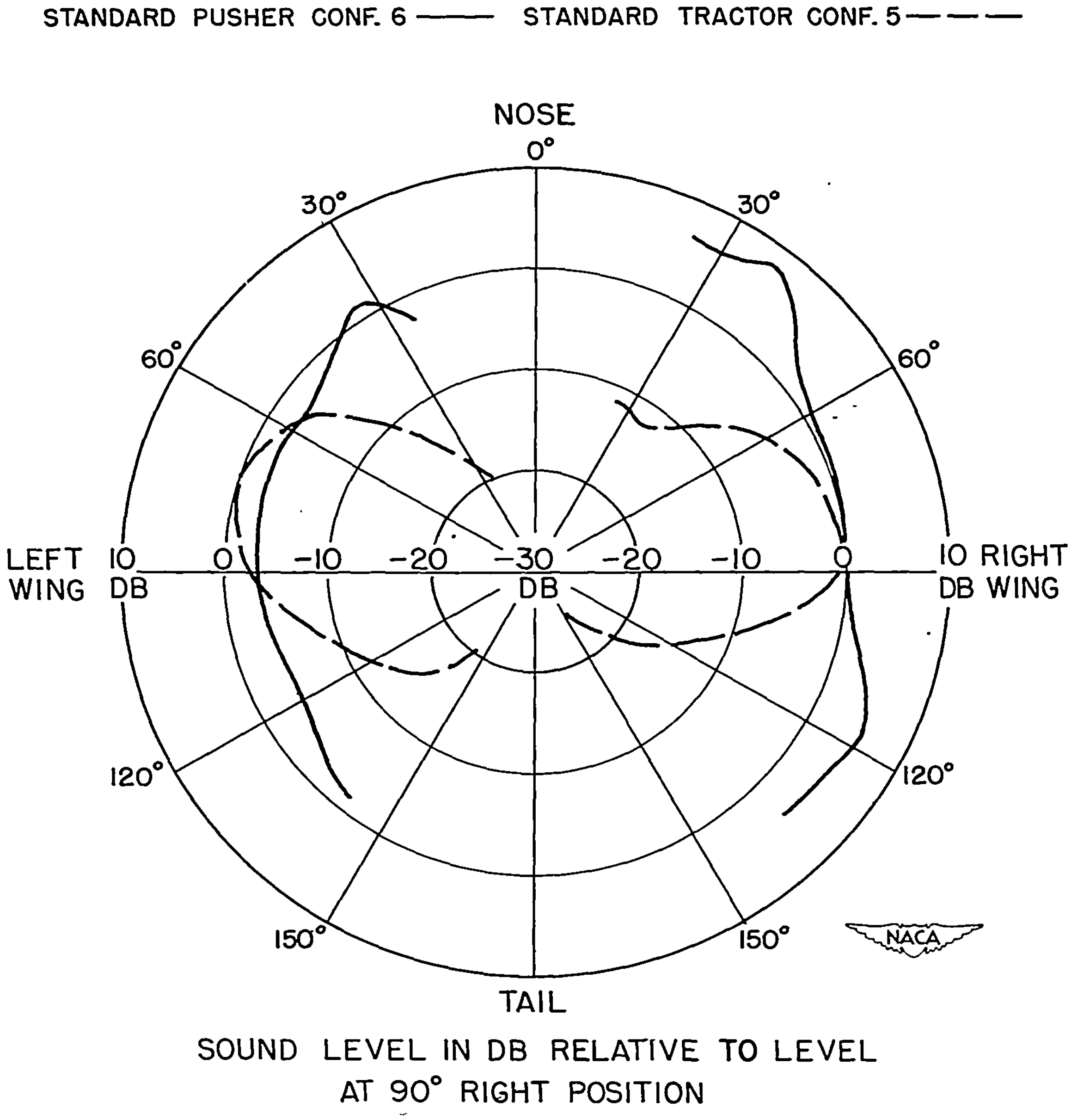
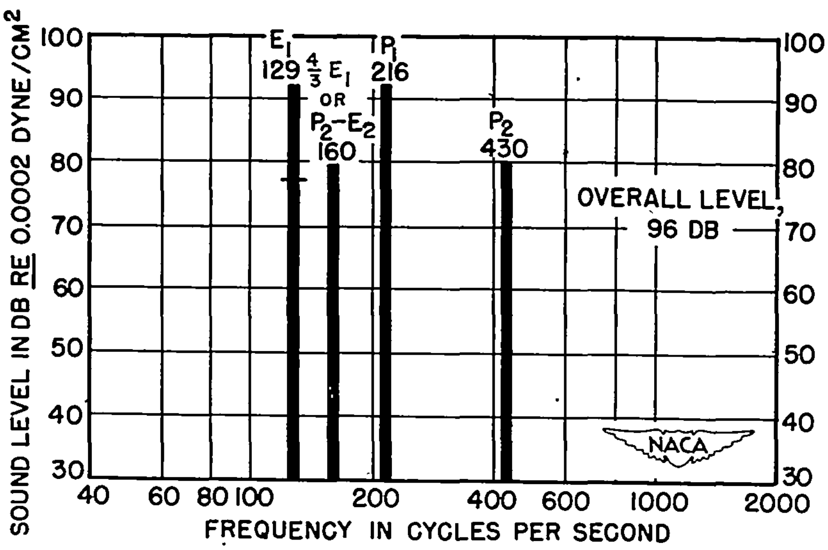
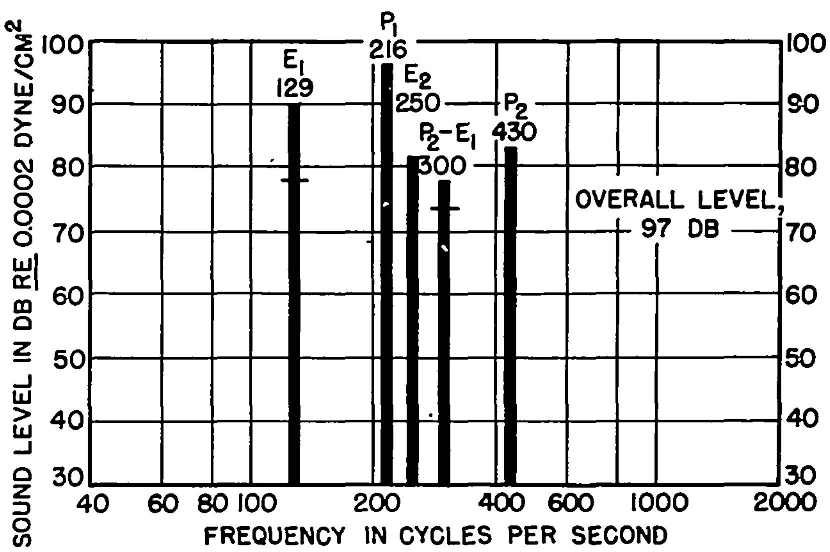


Figure 53.- Sketch of distribution of over-all noise level around standard configuration of series G in flight. Derived from figure 50; 40-decibel weighting.

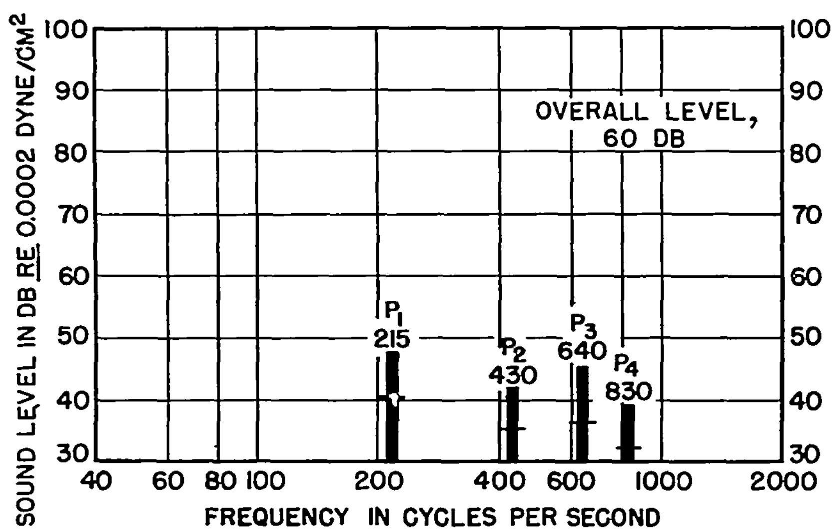


(a) Ground analysis. θ = 120° left of nose; s = 50 feet.

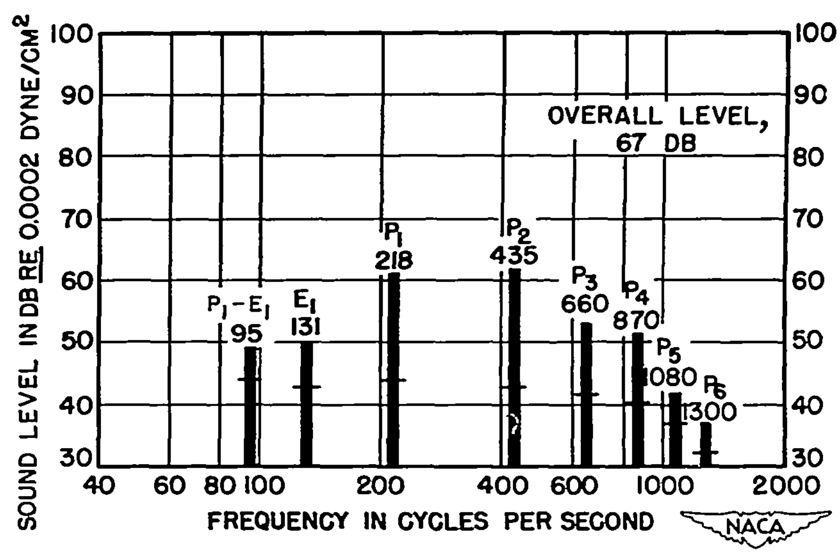


(b) Ground analysis. θ = 120° right of nose; s = 50 feet.

Figure 54.- Comparison of frequency analyses on ground 50 feet from hub with analyses of flights passing 3000 feet away for configuration of series H. Maximum power; flat weighting. θ, angle between direction of sound radiation from airplane and a line from tail to nose of airplane; s, distance from propeller hub to microphone; P_1, propeller fundamental; P_2 to P_6, propeller second to sixth harmonics; E_1, engine fundamental; E_2, engine second harmonic. Numbers above each bar indicate measured frequency; horizontal lines on bars indicate levels of background noise. RE indicates "referred to a level of."

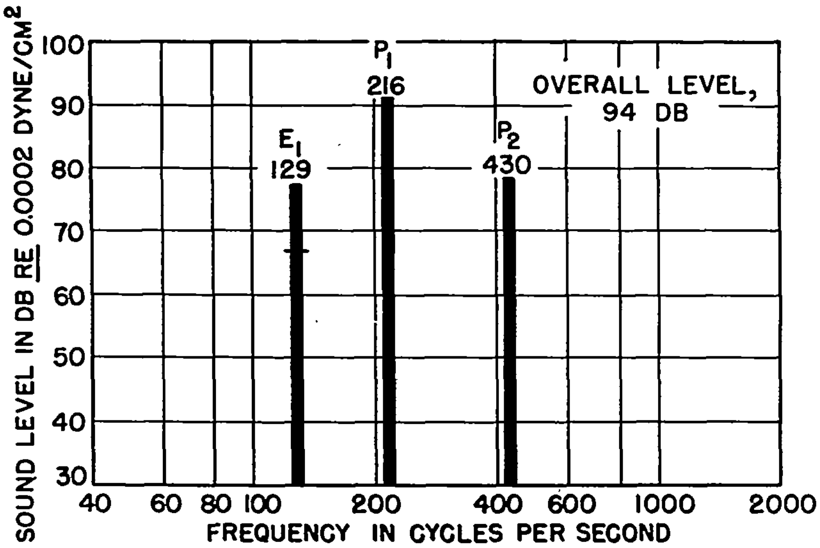


(c) Flight at 500-foot altitude. θ = 125° left of nose; s = 3750 feet.

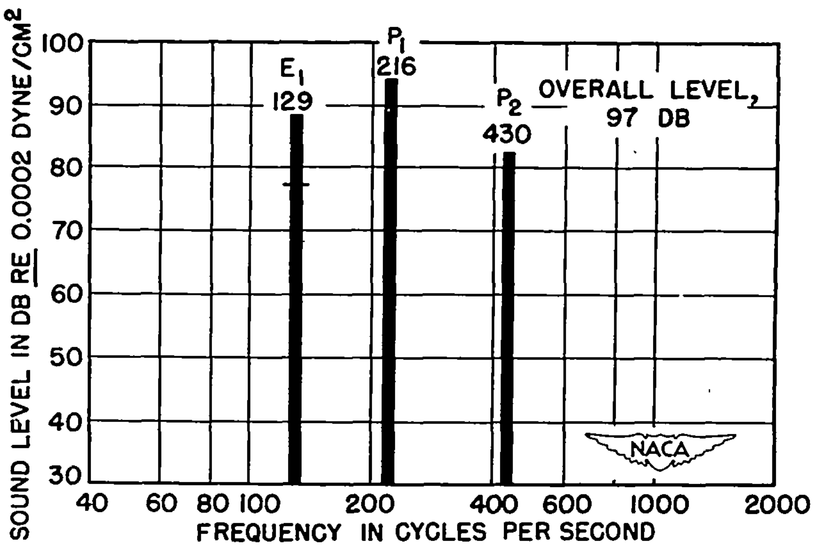


(d) Flight at 500-foot altitude. θ = 117° right of nose; s = 3400 feet.

Figure 54.- Continued.

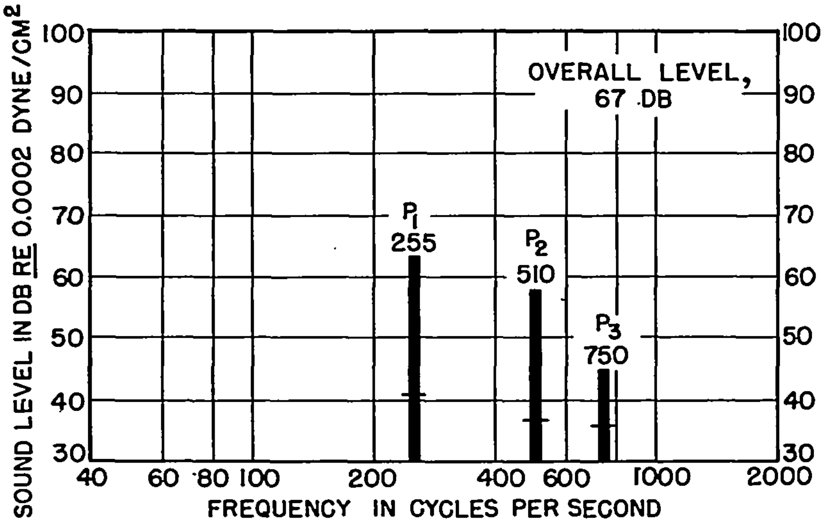


(e) Ground analysis. $\theta = 60^{\circ}$ left of nose; s = 50 feet.

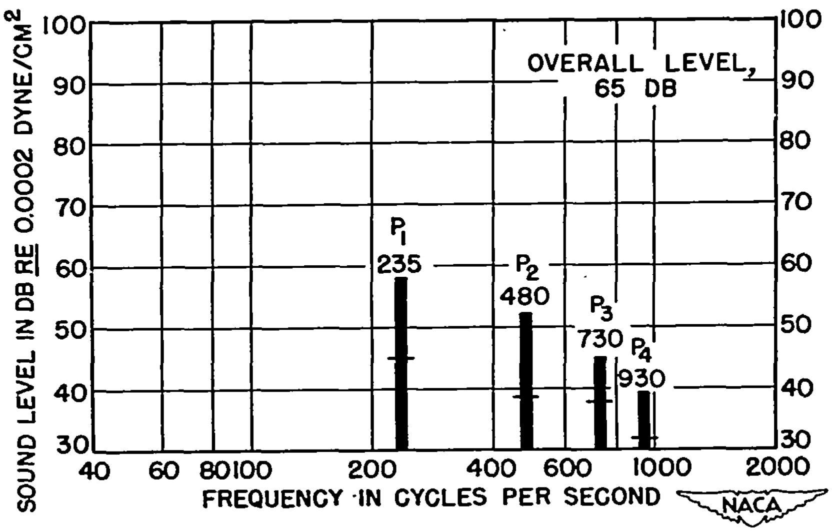


(f) Ground analysis. $\theta = 90^{\circ}$ left of nose; s = 50 feet.

Figure 54.- Continued.



(g) Flight at 500-foot altitude. $\theta = 47^{\circ}$ left of nose; s = 4050 feet.



(h) Flight at 500-foot altitude. $\theta = 80^{\circ}$ left of nose; s = 3040 feet.

Figure 54.- Concluded.

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